AN INTRODUCTION TO

GEOLOGY

(*PHYSICAL AND HISTORICAL*)

BY

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THIRD EDITION—FOURTH PRINTING

NEW YORK

D. VAN NOSTRAND COMPANY, INC.

250 FOURTH AVENUE

PRINTED IN THE U S A BY
THE PLIMPTON PRESS, NORWOOD, MASS.

FOREWORD

AN INTRODUCTION TO GEOLOGY is a single volume edition of Professor Miller's two books which have previously been published separately as AN INTRODUCTION TO PHYSICAL GEOLOGY and AN INTRODUCTION TO HISTORICAL GEOLOGY. This book is divided into two parts, the first devoted to a thorough discussion of the theories and principles of physical geology, and the second to a thorough analysis of the problems which confront the teacher of historical geology. Each part is an entirely distinct unit with separate folio numbers, separate indices, and separate illustrations each numbered in sequence. A preface precedes each part, outlining in some detail the author's method of treatment and arrangement of material.

It is hoped that this means of publication will prove convenient to those teachers who prefer a single volume for use throughout the year. It is not the purpose, however, of the publishers to take the two-volume work from the market, and the book may be procured either in its present form or as two separate volumes.

THE PUBLISHERS

Part I

AN INTRODUCTION TO PHYSICAL GEOLOGY

First Published, *September, 1924*
Reprinted, February, 1925, November, 1925

Second Edition, *September, 1927*
Reprinted, January, 1929, January, 1930

PRINTED IN THE U S A BY
THE PLIMPTON PRESS, NORWOOD, MASS.

PREFACE TO SECOND EDITION

In this second edition, a considerable number of corrections and minor alterations have been made while twenty of the illustrations have been replaced with better ones. Various teachers who use the book have very kindly offered valuable suggestions, and these have been carefully considered

Some objection to the order of the chapters in the first edition was raised, but most of the authorities who have been consulted in regard to this matter agree that the present arrangement is logical. The reasons for this arrangement are given in the preface to the first edition but, if an instructor so desires, it is relatively easy for him to follow some other order in assigning the chapters to his classes.

WILLIAM J. MILLER

University of California at
Los Angeles, California,
June, 1927

PREFACE TO FIRST EDITION

THIS "Introduction to Physical Geology" has been prepared as a companion volume to the author's "Introduction to Historical Geology." The two books together are intended to serve as a text for a one-year college course in general geology. For such a purpose, the two books may be procured bound in a single volume called "An Introduction to Geology." The present book may be used, however, as a text for special courses in physical geology. It may be adapted readily to shorter courses by the omission of certain portions, according to the judgment of the instructor.

The book has been so written that a formal knowledge of neither chemistry nor physics is a prerequisite for a reasonable understanding of its contents. The instructor ordinarily can supply the most needed information along these lines in the class-room and laboratory lectures and discussions

It is assumed that at least some laboratory and field work will be carried on in connection with the course. Field trips should be made to illustrate as many of the principles of the science as time and conditions will permit. Such out-door work greatly aids in making the study more realistic and interesting. Laboratory work should be, as far as possible, directly correlated with the class-room and text-book work. The student should study specimens of minerals and rocks, and also models, maps, and diagrams. Many laboratory problems and exercises may be devised along the general lines of United States Geological Survey Professional Paper No. 60, entitled "Interpretation of Topographic Maps." The Geological Survey has a wealth of topographic maps, any of which may be purchased singly or in duplicate at very small cost.

Concrete examples are freely used to illustrate important facts and principles, and, since geology is essentially an historical science, the historical order has been emphasized in the treatment of the special topics and concrete examples.

Careful attention has been given to the arrangement of the subject-matter. The very nature of the subject is such, however,

that some repetition and anticipation are unavoidable no matter what the arrangement. The purpose has been not only to make the order of treatment logical, but also to avoid repetition and anticipation as far as possible. With these ends in view, the materials of the earth — minerals and rocks — are first considered after the introductory chapter. This is because the subject of study is the earth, and a knowledge of the nature of its materials is fundamental to all that follows. In the writer's experience, it is well to begin the laboratory work in geology with a study of minerals and rocks, using the data in Chapters III and IV as a laboratory guide. Then the manner in which rocks weather, the movements to which they are subjected in the earth's crust, and their structural arrangement are taken up in regular order. The important chapter on the work of streams is then taken up much more satisfactorily, it is believed, than in most text-books because the knowledge of earth materials, weathering, earth-crust movements, and earth-crust structures already gained greatly aids in the understanding of certain important phases of river work. Glaciers, wind, sea, volcanoes, and underground waters are next discussed as geological agencies. Mountains, lakes, and economic geology are taken up last because a knowledge of so many principles of the science is necessary to a proper understanding of these subjects.

Much time and thought have been devoted to the gathering of the illustrations which form an essential part of the book. Most of them have never before appeared in any text-book. Many of the half-tones have been made from pictures taken by the author for the express purpose of illustrating the book. All of the views and diagrams illustrate important facts and principles of the science, and they should be, therefore, carefully studied in connection with the text.

Among the numerous original sources of photographs, special mention should be made of the United States Geological Survey, the United States Reclamation Service, the United States Forestry Bureau, the National Park Service, and the American Museum of Natural History. The Macmillan Company has generously permitted the use of several cuts.

The most important physiographic features and places referred to in the text are shown on the photographed relief map of North America, and on the map of the United States, in Chapter I. In

addition to these maps, the student should have at hand some good geography or atlas in order that other places and features mentioned and described can be definitely and readily located.

The author is under particular obligation to Professor J. A. Bownocker of Ohio State University for valuable suggestions, nearly all of which have been incorporated in the book. The author gratefully acknowledges his indebtedness to Associate Professor Aida A. Heine and Dr. Isabel F. Smith of the Department of Geology of Smith College for reading manuscript and offering suggestions. Conversations with various experienced teachers of geology also have been very helpful.

Due acknowledgment is here made for the help obtained from the various manuals, text-books, and special treatises on geology, and also from many publications of the United States Geological Survey.

Corrections and suggestions for the improvement of the book will be heartily welcomed.

WILLIAM J MILLER

UNIVERSITY OF CALIFORNIA, SOUTHERN BRANCH,
Los Angeles, California,
July, 1924

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WITH SPECIAL REFERENCE TO NORTH AMERICA

CHAPTER I

INTRODUCTION

DEFINITION OF GEOLOGY

GEOLOGY (meaning literally "earth science") deals with the history of the earth and its inhabitants as recorded in the rocks. Broadly considered, the science may be divided into physical geology and historical geology. *Physical geology* deals with the materials of the earth; earth-crust movements; the structure of the earth; and the processes and agencies by which the earth has been for many millions of years, and is being, modified, including such agencies as weather, wind, streams, glaciers, sea, organisms, volcanoes, subterranean waters, and lakes. *Historical geology* deals with the records of the successive events of earth history, and with the history and evolutionary changes of the organisms which have lived upon the earth. This book deals with physical geology only. *Geography* deals with the distribution of the earth's physical features, in their relation to each other, and to the life of sea and land, especially human life and activity. Geography may, therefore, be regarded as the outward and present-day expression of geological effects. Geology includes geography as cause includes effect.

THE EARTH AS A PLANET

Since the earth is our subject for study, it is important that the reader have clearly in mind certain well-known facts in regard to it as a planet. The earth is a member of the so-called solar system of which the sun, whose diameter is about 866,000 miles,

is the center. Eight planets, including the earth, revolve around the sun. The earth, whose diameter is nearly 8000 miles, rotates on its axis once in 24 hours. Its average distance from the sun is nearly 93,000,000 miles, and it revolves around the sun once in a little over 365 days. Certain planets are much larger and farther away from the sun than the earth, and some others are smaller and nearer the sun

One satellite, called the moon, revolves around the earth once in about 28 days. Although the moon is much smaller than the earth, nevertheless it has a considerable indirect geological influence upon the earth because it is the principal cause of ocean tides which latter have been of some importance for many millions of years of the earth's history.

The geological influence of the sun upon the earth is far greater than that of the moon because it is the chief source of the earth's light, heat, and energy which have made largely or wholly possible not only the work of rock weathering, streams, glaciers, and winds, but also plant and animal growth and progressive development.

The earth seems large, and it is very important to us as human beings, but it is very small as compared to the size of the solar system, and almost infinitesimal within the vast universe of which even the solar system is only a very small part.

The Great Parts of the Earth

The three great parts of the earth are the lithosphere, hydrosphere, and atmosphere. The lithosphere (meaning "rock sphere"), which consists of solid, rocky material, constitutes by far the greater portion of the earth, including not only the lands, but also the rocky materials under the oceans. The lithosphere is of supreme importance to the geologist because the records of the wonderful events of the earth's history are found in the rocks.

The partial envelope comprising all the waters on and near the earth's surface is called the hydrosphere. Most of the waters by far are in the oceans, but streams, lakes, and underground waters are also important. Water is one of the greatest of all geological agencies which, for countless ages, have been modifying the earth. Its greatest function is the wearing down (erosion) of the higher portions of the lithosphere, and the transportation and deposition

of the resulting sediment in the various lower portions (basins) of the lithosphere.

The gaseous envelope of the earth is called the atmosphere (air). To some extent it penetrates the outer portion of the earth's

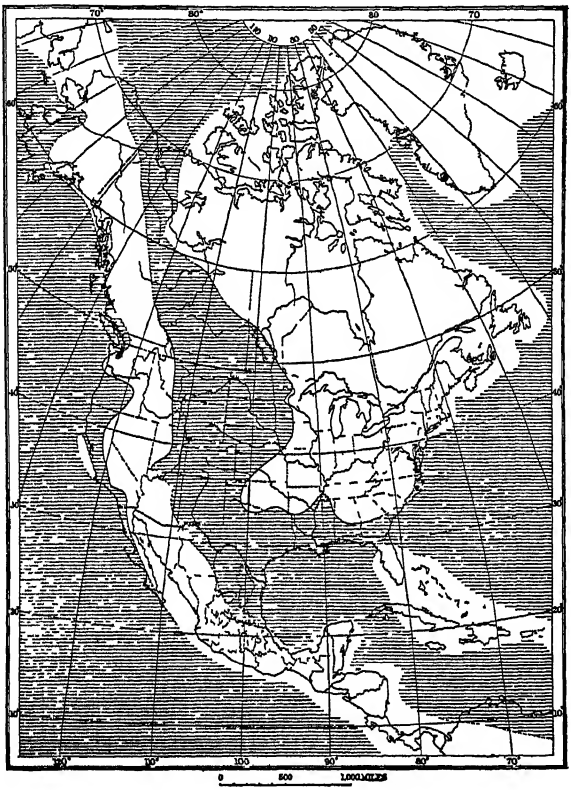

Fig. 1

Map of North America showing the relations of land and sea during part of Cretaceous time, millions of years ago (After C. Schuchert.)

crust through openings in the rocks, and to some extent it is dissolved in the waters. The chief constituents of the air are nitrogen, oxygen, water vapor, and carbon dioxide, all of which, excepting the first, effect important changes in the rocks and minerals

of the earth. Movements of the atmosphere (winds) cause important modifications of the lands, especially in arid regions. Probably the greatest geological function of the atmosphere is its making possible precipitation (rainfall and snowfall), which in turn makes possible the work of running water and glaciers.

The Scope and Significance of Geology

The person of ordinary intelligence is, unless he has devoted some study to the matter, very likely to regard the great variety of physical features and life of the earth as practically unchangeable, and to think that they were essentially the same in the beginning of the earth's history as they are now. But the study of geology has firmly established the great fact that the face of the earth, and the life upon it, represent merely a single phase of a tremendously long history which has involved many profound and far-reaching changes.

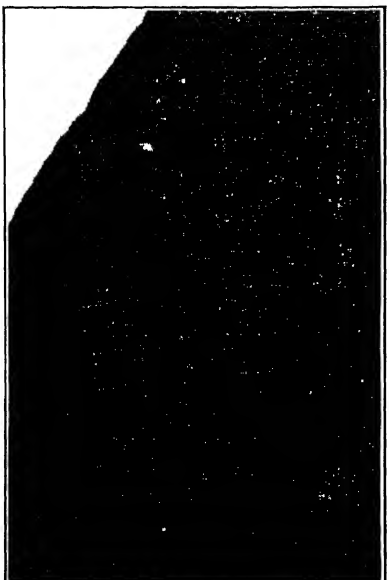

Fig. 2

A fossil sea-animal (Trilobite) at least 25,000,000 years old found 9000 feet above sea level in the Rocky Mountains (Photo by the author.)

The following concise statements of some of the more definite and important conclusions regarding earth changes may serve to give a fair conception of the general scope and significance of geology. For untold millions of years rocks at and near the surface of the earth have been crumbling under the weather; streams have been sawing incessantly into the lands; the sea has been eating into continental masses; the winds have been sculpturing desert lands; and, more locally and intermittently, glaciers have plowed

through mountain valleys, and even vast sheets of ice have spread over considerable portions of continents. The outer shell (so-called " crust ") of the earth has shown marked instability throughout geologic time. Slow upward and downward movements of the lands relative to sea level have been very common, in many cases amounting to thousands of feet. Various parts of the earth have been, and are being, affected by sudden movements

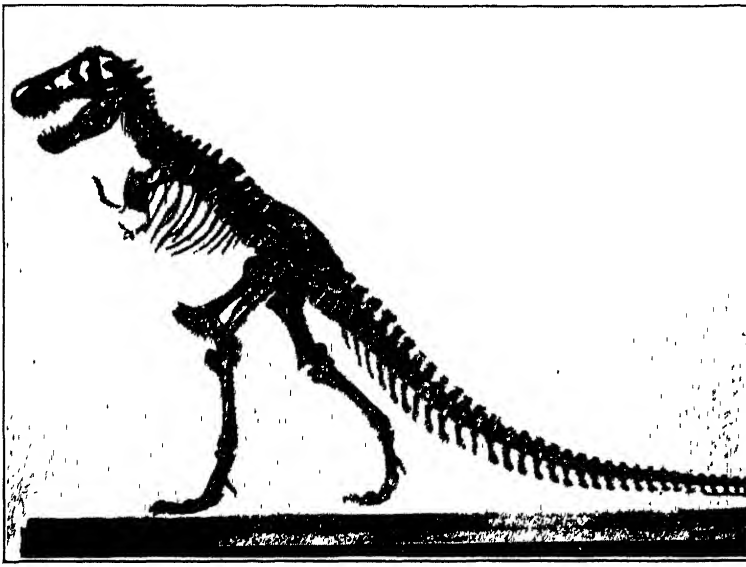

Fig 3

The skeleton of a great carnivorous reptile unearthed from rocks millions of years old. (Courtesy of the American Museum of Natural History.)

(resulting in earthquakes) along fractures in the outer crust. During the eons of geological time, vast quantities of molten materials have, at intervals, been forced not only into the earth's crust, but also often out upon the surface. Mountain ranges have been brought forth and cut down, and sometimes rejuvenated. Sea waters have spread over many parts of what are now continental areas. There have been repeated advances and retreats of the sea over many districts. Lakes have come and gone. Plants and animals have inhabited the earth for many

millions of years. In earlier known geological time the organisms were comparatively simple and low in the scale of organization. Through the succeeding ages higher and more complex types were gradually evolved until the highly organized forms of the present time, including human beings, were produced.

Geological Time

The great importance of the time element in the study of geology cannot be too strongly impressed upon the reader. The length of time of known human history is, indeed, very short as compared to that of known geological time. The one is to be measured by thousands of years, and the other by tens, or possibly hundreds, of millions of years. To the geologist a lapse of hundreds of thousands of years is a " short " time. " The flowing landscapes of geologic time may be likened to a kinetoscopic panorama. The scenes transform from age to age; seas and plains and mountains of different types follow and replace each other through time, as the traveler sees them succeed each other in space. At times the drama hastens, and unusual rapidity of geologic action has, in fact, marked those epochs since man has been a spectator upon the earth. (Geological) science demonstrates that mountains are transitory forms, but the eye of man through all his lifetime sees no (important) change, and his reason is appalled at the conception of a duration so vast that the millenniums of human history have not accomplished the shifting of even one of the fleeting views which blend into the moving picture " (J. Barrell).

The known history of the earth has been more or less definitely divided into great eras, and these in turn into periods and epochs. In the accompanying table, the era and period names, except those representing the earlier times, are mostly world-wide in their usage. Epoch names are too numerous, and usually too local in application, to be included in the table for our general use in this book. It will be well for the reader to learn at least the names of the eras, and to refer to the table whenever, in the study of the text, he is in doubt concerning any part of it.

How does the geologist determine the geological age of a given rock formation? This very important question is solved by methods of historical geology. Very briefly stated, however, two fundamental principles are involved. First, the order of

succession of stratified rock formations is determined, the older strata underlying the younger because they were first deposited. Second, each period and epoch of geologic time (except the very oldest) is known to have had a characteristic assemblage of organisms. A consideration of the characteristic fossil content of any set of strata, therefore, in direct connection with order of succession (superposition) of the larger pile of strata to which the set belongs, serves to determine the relative position of the set of strata (or formation), and hence its geological age.

TABLE OF MAIN GEOLOGICAL DIVISIONS

Estimated Minimum Duration	*Eras*	*Periods*	*Characteristic Life*	
3 to 5 million years	Cenozoic	Quaternary Tertiary	Age of man Age of mammals.	Age of highest order of plants and animals
5 to 10 million years	Mesozoic	Cretaceous Jurassic Triassic	First high order flowering plants. First birds and modern fishes First mammals (very primitive)	Age of reptiles and cycad plants.
15 to 25 million years	Paleozoic.	Permian Pennsylvanian Mississippian	Age of amphibians first insects, and first reptiles Great coal age (Pennsylvanian) with large, non-flowering plants.	
		Devonian	Age of primitive fishes, and first-known (very primitive) land plants	
		Silurian Ordovician Cambrian	Age of invertebrate animals, first (very primitive) vertebrates in Ordovician, and no known land animals	
Many millions of years	Proterozoic	Algonkian.	Meager records of relatively simple invertebrate animals, and very simple plants	
Many millions of years.	Archeozoic.	Archean	Primitive life, no determinable fossils	

Branches of Geological Science

It has already been suggested plainly that geology is very broad in its scope, and so with this general science, as with most

Fig 4
Relief Map of North America. (Courtesy of the United States Geological Survey.)

other great departments of human knowledge, a number of more or less separate branches of geology have come into existence as special fields of study. Most of the principal branches are as follows:

Mineralogy is the study of minerals which are natural, homogeneous substances of definite (chemical) composition. With the exception of a relatively very slight amount of organic material, minerals constitute the whole lithosphere as far as it is known.

Petrology is the study of rocks, which are more or less extensive constituents (or formations) of the earth's crust, and which are nearly always made up of mixtures of minerals, or, more rarely, of masses of single minerals.

Dynamical geology is the study of the agencies and processes whereby the outer portion of the earth has been, and is being, modified Important dynamical agents are weather, wind, running water, the sea, glaciers, igneous actions, and earth-crust movements.

Physiography, sometimes called *physical geography*, deals with the topography of the earth's surface and the manner of its origin. It is closely related to dynamical geology because it involves a consideration of the same modifying forces

Structural geology is the study of the arrangement or architecture of the materials of the earth. In a real sense it includes a study of the materials themselves, especially the rocks, and so it may be regarded as including petrology, and possibly mineralogy.

Paleontology deals with the plant and animal life of the geological ages as shown by the fossil remains of organisms found in the rocks.

Stratigraphy deals with the arrangement and succession of the strata of the earth.

Paleogeography deals with the geographic conditions of the earth during former (geologic) ages, especially with the relations of lands and seas. Paleontology, stratigraphy, and paleogeography are really subdivisions of *historical geology*, which, as already defined, deals with the successive events of earth history, including the history of organisms.

Economic geology is the practical application of geology to the arts and industries. It deals with geological products of value to mankind, such as coal, petroleum, ores of the metals, building stones, salt, gypsum, etc.

Geography, as already defined, is, in a broad sense, a branch of geology because it is the outward and present-day expression of geological effects. It is, however, often treated as a separate department of knowledge.

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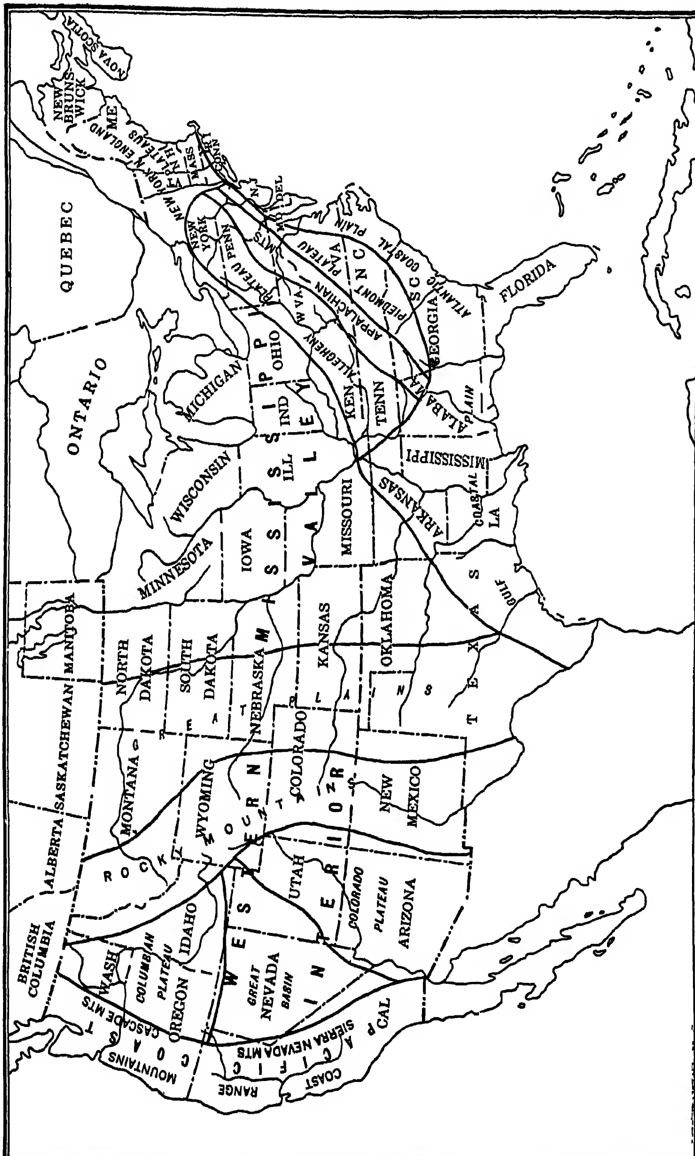

Fig. 5
Map of the United States showing the principal physiographic provinces. (By the author.)

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Russell: *Lakes of North America* (Ginn & Co , 1897).

CHAPTER II

MATERIALS OF THE EARTH — MINERALS [1]

Definition and Significance of Minerals

Minerals are, with slight exceptions, the materials which constitute the known parts of the earth. Mineralogy is, therefore, in a very real sense the most fundamental of the various branches of the great science of geology because the events of earth-history, as interpreted by the geologist, are recorded in the mineral matter (including most rocks) of the earth. When we examine the rocky material or mineral matter of the earth in any region we find that it consists of various kinds of substances, each of which may be recognized by certain characteristics. Each definite substance (barring those of organic origin) is called a mineral. Or, more specifically, a *mineral* is a homogeneous substance of definite chemical composition found ready-made in nature and not a product of life. According to this definition, a mineral must be a natural, inorganic substance of the same nature throughout, and its composition must be so definite that it can be expressed by a chemical formula.

All artificial substances, such as laboratory and furnace products, are excluded from the category of minerals because they have taken no part in the history of the earth. Coal is not a mineral both because of its variable composition and its organic origin. A few examples of very common substances which satisfy perfectly the definition of a mineral are quartz, feldspar, mica, calcite, and magnetite. More than a thousand mineral species are known. To these, and their varieties, several thousand names have been given. Not more than forty or fifty of the many minerals are, however, of great geological importance, and of these only six or eight make up more than ninety per cent of the outer

[1] Considerable portions of this chapter are taken by permission from Chapter XX of the present author's *Geology: The Science of the Earth's Crust*, which forms Volume 3 of Popular Science Library published by P. F. Collier & Son Company.

or crustal portion of the earth. Only two minerals — water and mercury — ordinarily exist in liquid form.

Chemical Make-up of Minerals

It is a surprising fact that of the ninety or more *chemical elements*, that is, substances which cannot be subdivided into simpler ones, only eight make up more than ninety-eight per cent of the weight of the earth's crust. It is important to note, however, that, with one very slight exception, none of the eight exists as such in mineral form. These eight elements are oxygen (nearly fifty per cent), silicon (over twenty-five per cent), aluminum (over seven per cent), iron (over five per cent), calcium (or "lime"), magnesium (or "magnesia"), sodium (or "soda"), and potassium (or "potash"). Among other elements found in useful or common minerals are carbon, hydrogen, sulphur, chlorine, fluorine, phosphorus, barium, copper, gold, lead, mercury, platinum, silver, tin, and zinc. Some of the elements last named may exist as such in nature, as for example, gold, copper, silver, carbon (in form of graphite and diamond), sulphur, and platinum.

In most cases by far two or more of the chemical elements are variously combined in such a manner (chemically) as to lose their identities as such. Thus the two vicious substances sodium and chlorine are combined to form the beneficial mineral called halite or common salt (composition, chloride of sodium). Oxygen and silicon (a gas and a solid) may be united to form the very hard, common mineral called quartz (composition, oxide of silicon). Three elements — calcium, carbon, and oxygen — are united in the common mineral known as calcite (composition, carbonate of lime). Four elements — potassium, aluminum, silicon, and oxygen — are chemically combined in the exceedingly common mineral known as orthoclase feldspar (composition, potassium aluminum silicate). Some other minerals are still more complicated in composition.

Geological Importance of Minerals

Certain rock formations are made up essentially of but one mineral in the form of numerous individual grains, as for example pure limestone which may consist wholly of calcite (carbonate of lime), or pure sandstone which may contain only grains of quartz

(oxide of silicon). Most of the ordinary rocks are, however, made up of two or more minerals mechanically bound together. Thus, in a specimen of granite on the author's desk, several distinct mineral species are distinguishable by the naked eye. These mineral grains are from one to five millimeters across. Most common among them are hard, clear, glassy grains, called quartz; nearly white, hard grains, often with smooth faces, called feldspar;

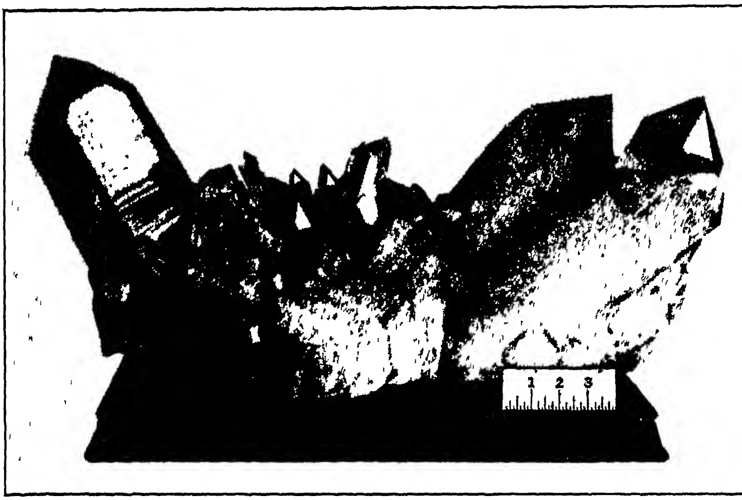

Fig. 6
A group of quartz crystals (Courtesy of the American Museum of Natural History.)

small, silvery white flakes, called mica; and small, hard, black grains, called magnetite.

It is the business of the mineralogist to learn the characters of each mineral, how they may be distinguished from each other, how they may be classified, how they are found in nature, how they originate, and what economic value they may have. It is an important part of the business of the geologist to learn what individual minerals combine to form the various kinds of rocks (described in Chapter II), how such rocks originate, what changes they have undergone, and what geological history they record. It is thus clear that mineralogy is an important part of geology, which latter is essentially the science of rocks.

Crystal Forms of Minerals

One of the most remarkable facts about minerals is that most of them by far have a crystalline structure, that is they are built up of definitely arranged tiny particles known as molecules. Crystalline minerals are often more or less regular, solid forms bounded by plane faces and sharp angles, such forms being known as *crystals* (Fig. 6). How do crystals develop such regularity of form? Any solid is considered to be made up of many very tiny (sub-microscopic) molecules held together by an attractive force called cohesion. In liquids the molecules may more or less freely roll over each other, thus altering the shape of the mass without disrupting it. In gases the molecules are considered to be rela-

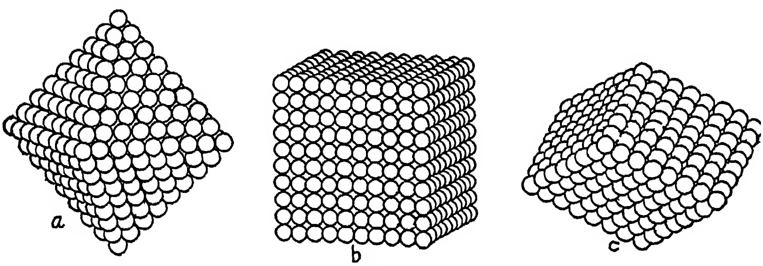

Fig. 7

Piles of shot illustrating the molecular structure of crystals (After Whitlock, New York State Museum)

tively long distances apart and moving rapidly. During the process of change of a substance from the condition of a liquid or a gas to that of a solid, due to lowering of temperature or evaporation, the cohesive force pulls the particles (molecules) together into a rigid mass. Under favorable conditions such a solid possesses a regular polyhedral form.

The process of crystallization has been clearly suggested by Whitlock who says: " This results from the fact that particles or molecules of the substance which, while it was liquid or gaseous, rolled about on one another, have been in some way arranged, grouped, and built up. To illustrate this, suppose a quantity of small shot to be poured into a glass: the shot will represent the molecules of a substance in a liquid state, as for example a solution of alum. If, now, we suppose these same shot to be coated with varnish or glue so that they will adhere to each other, and imagine

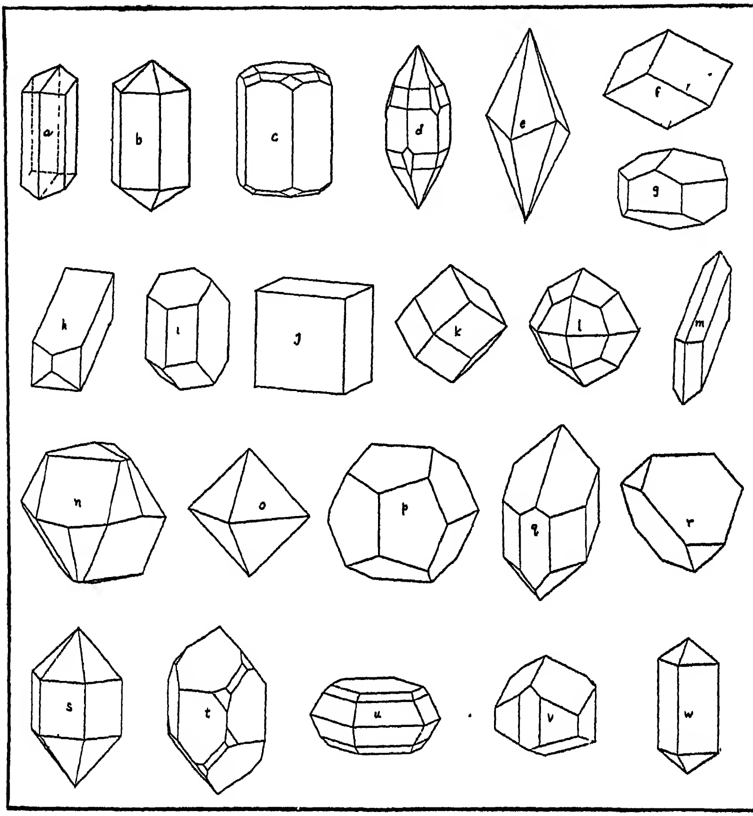

Fig 8

Crystal forms of some common minerals *a*, amphibole; *b*, apatite; *c*, beryl; *d*, corundum; *e*, *f*, *g*, calcite; *h*, *i*, feldspar; *j*, fluorite; *k*, *l*, garnet; *m*, gypsum; *n*, hematite; *o*, magnetite; *p*, pyrite; *q*, pyroxene; *r*, chalcopyrite; *s*, *t*, quartz; *u*, sulphur; *v*, tourmaline; *w*, zircon. (After New York State Museum.)

them grouped as shown in Figure. 7a, they will represent the arrangement of the molecules of the alum after it has become solid or crystallized. This arranging, grouping, and piling up of molecules is called *crystallization*, and the solid formed in this way is called a *crystal*. Figures 7b and 7c show the shot arranged to reproduce two common forms of crystals (e.g. fluorite and calcite)."

Certain facts furnish all but absolute proof of regularity of arrangement of particles within crystals. Among these facts are the wonderful regularity (*symmetry*) of faces upon crystals; the remarkable property of most crystals to split (cleave) readily in certain directions; the grouping of crystals according to characteristic effects of the passage of light (especially of polarized light) through them; and x-ray photographs showing systematical arrangement of groups of particles within crystals.

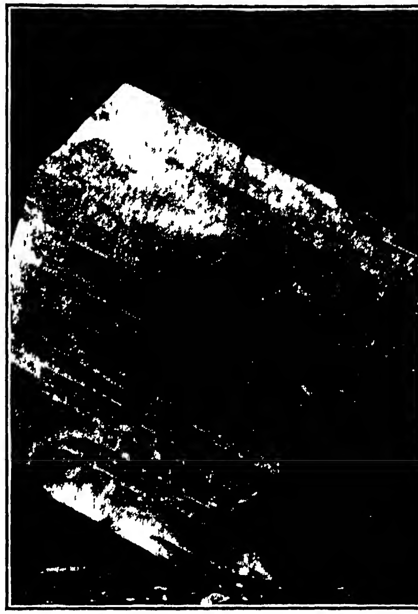

Fig. 9
Part of a crystal of calcite showing three well-developed cleavages. (Photo by the author.)

All crystals may be grouped into seven systems, each characterized by a certain type of arrangement of crystal faces, angles, and edges about imaginary lines (axes) which run through the center of the crystal. Each system contains from two to seven classes of symmetry, there being thirty-two in all. Each class contains seven fundamental crystal forms. Thus, two of the seven fundamental forms of the class to which garnet belongs are represented by Figures 8k and 8l. Figure 8 illustrates perfect crystal forms of a number of common and useful minerals.

Physical Properties of Minerals

Cleavage. — Many crystals and crystalline substances exhibit the important property known as *cleavage*, that is, a marked tendency to break or split easily in certain well defined directions yielding more or less smooth surfaces. A cleavage surface is, as

would be expected, always parallel to an actual, or at least a possible, crystal face, because the splitting occurs along planes of weaker molecular cohesion. The degree of cleavage varies from almost perfect, as in mica, to very poor or none at all, as in quartz. The number of cleavage directions exhibited by common minerals is illustrated by the following mica, one; feldspar and amphibole, two; calcite (Fig. 9) and galena, three; fluorite, four; and sphalerite, six. In the study of mineral specimens, careful attention should be given to cleavage whenever it occurs, for certain minerals always show certain cleavage directions.

Hardness. — An important criterion for the recognition of minerals is *hardness*, by which is meant the degree of resistance which a smooth mineral surface offers to abrasion or scratching. Scarcely any two minerals are just alike in hardness, but for practical purposes a generally adopted scale recognizes ten degrees of hardness as follows:

1. Soft, greasy feel, and easily scratched by the finger nail (e g. talc).
2. Just scratched by the finger nail (e.g gypsum).
3. Just scratched by a copper coin (e.g calcite).
4. Easily scratched by a knife, but does not scratch glass (e.g. fluorite).
5. Just scratches common glass, and is scratched by a knife (e.g. apatite).
6. Not scratched by a knife and scratches common glass easily (e.g. orthoclase feldspar).
7. Much harder than steel, and scratches hard glass easily (e g quartz).

8, 9 and 10 Harder than any ordinary substance, and represented in order by topaz, corundum, and diamond.

Color. — Minerals show a great variety of colors. Many of them, like pure quartz, gypsum, halite, and calcite, are colorless or white. Many of them, like galena (steel-gray), pyrite (brass-yellow), azurite (blue), malachite (green), magnetite (black), and cinnabar (red), possess these colors as inherent characteristics which never fail. Still others, like amethyst (purple) and sapphire (blue) are colored by impurities.

Lustre. — *Lustre* is the appearance of the surface of the mineral independent of the color. It is often more or less characteristic

of a mineral such as metallic, glassy, resinous, greasy, dull, brilliant, etc.

Transparency. — A mineral is said to be transparent when an object can be seen clearly through it, translucent when it transmits light but an object cannot be seen through it; and opaque when it transmits no light.

Streak. — Certain of the colored minerals are colored differently when in powdered form. A simple way to get a little of the powdered mineral is to rub the specimen on a piece of unglazed porcelain (so-called "streak-plate"). The *streak* so obtained may be characteristic of the mineral, and this greatly aids in identifying the species. Thus, black hematite gives a red streak; black limonite a yellowish brown streak; yellow pyrite a greenish black streak; etc.

Weight. — Minerals vary greatly in weight, each one having its own characteristic specific gravity, that is, weight in proportion to that of an equal volume of water. The range is from less than 1 to about 23. The average specific gravity of all minerals is about 2.6. It is important to note the relative weight of the specimen examined because it often aids in recognizing the species.

Some Common and Useful Minerals

A reasonable acquaintance with the more common and useful minerals can be gained only by a study of actual specimens In the following list, alphabetically arranged for convenience of reference, only the more obvious, easily determinable properties of each mineral are listed.

Amphiboles. — A number of species related in composition, crystal form, and properties are here included They are mostly very complicated compounds of silicon, oxygen, lime, and magnesia, usually also with aluminum and iron. The most common and important one is called *hornblende*. It crystallizes with well-defined prismatic faces (Fig 8), and with two good cleavages crossing at angles of about 124° and 56° and parallel to the prismatic faces. Color, dark brown to black Transparent to opaque. Hardness, nearly 6. Specific gravity, over 3. It is a very common mineral, especially in igneous and metamorphic rocks.[1] Much less common varieties of amphibole are *tremolite*, colorless to light gray, and common in metamorphic

[1] There are three great classes of rocks. (1) igneous, comprising materials which were once molten; (2) sedimentary, comprising those which have been deposited by ice, wind, or water (chiefly the last), and (3) metamorphic, comprising igneous or sedimentary rocks which have been altered profoundly from their original condition. The more common kinds of rocks are described and explained in Chapter II.

limestones; actinolite, a green variety common in some metamorphic rocks one kind of *asbestos* which is a very fibrous mineral, and one kind of *jade* which is white, gray or green and very tough

Apatite. — Composition a combination of phosphorus, oxygen, and lime Crystallizes in regular six-sided prisms capped at each end by a six-sided pyramid (Fig 10) Color variable, but usually green or brown Transparent to opaque. Hardness, 5 No good cleavage Specific gravity, 3 2 Rather widely disseminated in many common kinds of rocks Apatite, mainly in uncrystallized form, is the chief source of phosphate fertilizer

Fig 10

A crystal of apatite on limestone. (Courtesy of Katharine Bryant)

Azurite. — Composition a compound of copper, hydrogen, carbon, and oxygen. Commonly crystallized in tabular and prismatic forms. Color, characteristic azure-blue Translucent to opaque. Hardness, nearly 4. Specific gravity, nearly 4. No good cleavage. Commonly occurs in veins.[1] It is an ore of copper, as for example in some of the copper mines of Arizona.

Barite. — A compound of barium, sulphur, and oxygen crystallizing in tabular prismatic forms. Often called "heavy spar" because of its specific gravity of 4 5 which is notably greater than that of the average light-colored mineral. It has three good cleavages, two of them at right angles. White or colorless when pure Transparent to opaque. Hardness, 3.5. It is a com-

[1] Veins are fissures in the earth which have been filled with mineral matter from solutions.

mon mineral, especially in vein deposits, often associated with ores[1] Used in powdered form to give added weight to certain kinds of paper and cloth. It is the source of a barium compound used to refine sugar.

Beryl. — Composition a complex combination of silicon, oxygen, aluminum, and the rare element beryllium Usually crystallizes in regular six-sided prisms, sometimes a foot or more long (Fig. 8) Color, usually white, green, blue or yellow. Transparent to translucent Specific gravity, 2.8. Practically no cleavage Very exceptionally hard, being 8 in the scale.

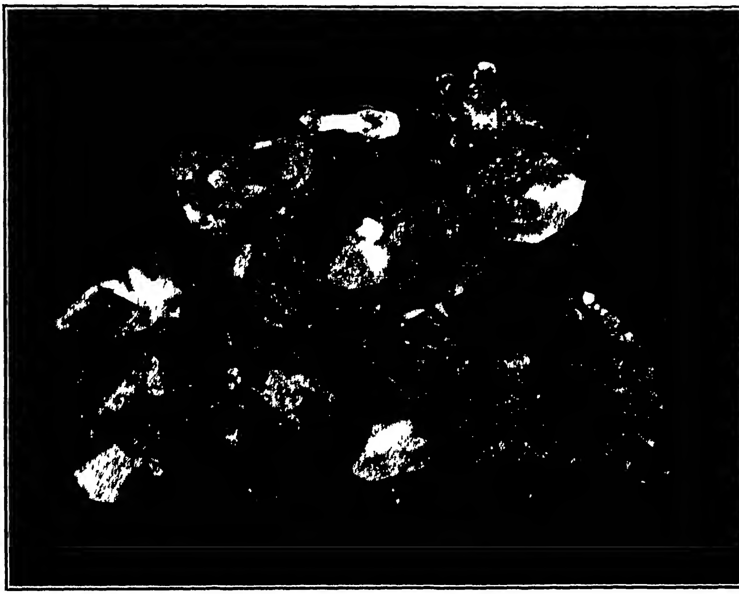

Fig. 11
A group of calcite crystals. (Courtesy of the American Museum of Natural History.)

Two varieties of beryl — *emerald* (green) and *aquamarine* (blue) — are well-known and highly prized gem stones. The colors are due to slight impurities. Beryl occurs most commonly in a special kind of coarse grained granite, and in metamorphic rocks

Calcite. — Sometimes called "calc spar" Composition: a combination of lime, carbon, and oxygen (i e. a carbonate of lime). Exhibits a great variety of crystal forms, but all of them with crystal faces arranged in sixes or threes around a principal axis. Figures 8 and 11 illustrate a few of the most common shapes. Three almost perfect cleavage directions, none meeting at right angles (Fig. 9). Color, white or colorless when pure, but of various shades

[1] An ore is a metal-bearing mineral of economic value.

when impure. Transparent to opaque Hardness, 3 Specific gravity, 2 7. Bubbles freely when touched with a drop of cold, dilute, hydrochloric acid. Calcite is a very common mineral especially because much limestone (including *chalk*) and marble usually consist largely of it Very common as vein fillings (Fig 298). Also often occurs in the form of a stringy, porous spring deposit called *travertine*, and as cave deposits such as *stalactites* and *stalagmites* (Fig 297) A very clear, crystalline variety is *Iceland spar* Calcite is a very useful mineral widely employed in the form of limestone and marble for building stone, decorative purposes, etc Also used in making quicklime, as a flux in smelting certain ores, in glass making, etc.

Cassiterite. — Composition: a simple compound of tin and oxygen Crystallizes in four-sided prisms capped with pyramids Hardness, over 6 (greater than steel) Specific gravity, 7 (notably high) Color, brown to nearly black Translucent to opaque Practically no cleavage Usually occurs in granite or metamorphic rocks near granite, and also in gravel deposits, as in the important mines in the Malay region It is the one great ore of tin.

Chalcocite. — Composition a simple compound of copper and sulphur Crystallizes in flattish prismatic forms, but usually not crystallized. Shiny black with metallic lustre, and tarnishes on exposure to air to dull black Opaque. Hardness, nearly 3 Specific gravity, nearly 6 (notably high) No cleavage Occurs in vein deposits often as an important ore of copper, as at Butte, Montana

Chalcopyrite. — Sometimes called "copper pyrites" Composition: a simple compound of copper, iron, and sulphur Crystallizes in four-sided tetrahedron-like forms, but good crystals are not common Color, characteristic deep brass-yellow with metallic lustre Opaque. Hardness, 3.5. Specific gravity, over 4 Rather widely distributed, usually in vein deposits, often associated with other metal-bearing minerals. It is a very important ore of copper, as at Rio Tinto, Spain.

Cinnabar. — Composition mercury and sulphur chemically united. Color, characteristic vermilion-red. Transparent to opaque. Hardness, 2.5, being an extra-soft metal-bearing mineral. Specific gravity, over 8, being extra-heavy. Small three-sided crystals are rare Completely vaporizes on being heated It is the one great ore of mercury (quicksilver), especially in California and Spain.

Copper. — Known as "native copper" Composition. copper only. Color, characteristic copper-red, with metallic lustre. Opaque. Hardness, less than 3. Specific gravity, nearly 9, being extra-heavy. Cubic and modified cubic crystals are not common Rather widely distributed, usually in veins It is an important ore of copper, especially in the great mines of Northern Michigan.

Corundum. — Composition: a simple combination of aluminum and oxygen Crystallizes in six-sided prisms capped with very steep pyramidal faces (Fig. 8) Hardness, 9, being among the few very hardest of all known minerals. Specific gravity, about 4. Three good cleavages make angles of nearly 90° with each other Color, usually gray to brown, but varies greatly. Transparent to opaque Two of the most highly prized precious stones — *ruby* (red) and *sapphire* (blue) — are nearly transparent, slightly impure

varieties of corundum *Oriental topaz* (yellow), *oriental emerald* (green), and *oriental amethyst* (purple) are also varieties of corundum. *Emery* is a fine grained, gray, crystalline variety of corundum usually mixed with magnetite, etc Corundum occurs in various igneous and metamorphic rocks, and also in gravel deposits, as in the sapphire and ruby mines of Burma, Siam, and Ceylon Emery was formerly mined in Asia Minor, Massachusetts, and California for use in the manufacture of abrasives

Diamond. — Composition pure carbon. Crystallizes in octahedral forms Colorless when pure, but often variously tinted, one variety being almost black Transparent to opaque. Exceedingly brilliant lustre. Hardness, 10, being the hardest known substance Cleaves in four directions parallel to the octahedral crystal faces. Specific gravity, 3.5 Burns away completely at high temperature Found in a peculiar kind of igneous rock in the great mines of South Africa Also occurs in gravel deposits, as in Brazil and India.

Fig 12

A group of feldspar (microcline) crystals. (Photo by the author.)

Dolomite. — Composition a combination of lime, magnesia, carbon, and oxygen Crystals are usually six-sided rhombohedrons (Fig 8) Three cleavage directions, much as in calcite. Hardness, nearly 4 Specific gravity 2 8 Colorless or white when pure, but variously colored by impurities Translucent to opaque. Often difficult to distinguish off-hand from calcite, but it does not bubble when touched with a drop of cold dilute hydrochloric acid. It is a common and widespread mineral, especially in vein deposits, and in certain kinds of limestone and marble

Feldspars. — Here are included a number of mineral species and varieties, all very closely related in composition and properties. They are all compounds of aluminum, silicon, and oxygen with either potash, soda, or lime. All have common properties as follows· Color, usually white, gray, or pink; transparent to opaque; crystals in form of prisms with faces meeting at or near 90° or 120° (Fig. 12); two good cleavages at or near 90°; hardness at or near 6; and specific gravity of about 2.6, which is the average for all minerals. The most common potash feldspar is *orthoclase*, with two cleavages at exactly 90°. The soda-lime feldspars go by the general name of *plagioclase*. They are slightly different from orthoclase in crystal form and have cleavages at ap-

proximately 86° Very commonly cleavage faces in one of the two direction show fine parallel lines caused by a peculiar development (called "twinning" during the crystal growth Among the several varieties of plagioclase are *albite*, including most *moonstone*, and *labradorite* which is usually gray to greenish gray with a beautiful play of colors Feldspars are by far the most abundant minerals of the earth's crust They occur in all of the three great groups of rocks — igneous, sedimentary, and metamorphic — but their most common home is in the igneous rocks, as for example granite Potash feldspar is used in the manufacture of porcelain and chinaware Special varieties are used as semiprecious stones or for decorative purposes

Fig. 13

Galena crystals (Photo by the author.)

Fluorite. — Often called "fluor spar" Composition a simple combination of lime and fluorine Commonly found in the form of cubic crystals Colorless when pure, but variously, and often beautifully colored, especially blue, green, purple and yellow, due to impurities in solution during crystallization. Transparent to translucent Four well-developed cleavages meeting at such angles as to permit octahedrons of very regular shape to be broken out of crystals Hardness, 4. Specific gravity, over 4 Very common in vein deposits, often associated with ores Some veins in mines of Southern Illinois are 20 to 40 feet wide Mostly used in the manufacture of glass, enamel ware, and a certain kind of steel.

Galena. — Composition: a simple combination of lead and sulphur Crystals are most commonly cubes (Fig 13) and octahedrons. Color, lead-gray with metallic lustre which tarnishes dull. Opaque Hardness, 2.5. Specific gravity, 7.5 (notably high) Very brittle. Three excellent cleavages at right-angles, and parallel to the cubic crystal faces It is the one great ore of lead, being mined in many parts of the world, as for example Missouri, Colorado, Idaho, and the Rhine district

Garnets. — The term "garnet" includes a number of mineral species or varieties very closely related in composition, crystal form, and physical properties. Composition. compounds of silicon, oxygen mostly with aluminum and either lime, magnesia, or iron. Crystals are thickset, usually with 12 or 24 faces, or a combination of the two (Fig. 14). Cleavage, scarcely noticeable.

Hardness, 6 5 to 7 5 (extra high). Specific gravity, 3 1 to 4 3 Hardness and specific gravity vary according to species. Color varies with composition; but mostly red, brown, black, or green Transparent to opaque. Garnets are mostly found in metamorphic and igneous rocks Used as a precious stone, and also in the manufacture of so-called "garnet paper" which is similar to "sandpaper"

Gold. — Known as "native gold" Composition pure gold. Crystals are usually thickset, octahedral forms, but they are rare No cleavage. Color, characteristic gold-yellow Opaque Hardness, less than 3. Specific gravity, over 19, being exceedingly high. Extremely malleable Gold is, in small amounts, very widely distributed. Most of it occurs in gravel ("placer") deposits, and in vein deposits

Fig. 14
Garnet crystals in schist. (Photo by the author)

Graphite. — Commonly called "black lead," but it is not lead at all Composition: pure carbon — the same as that of the diamond, but with strikingly different physical properties. Color, black with metallic lustre Opaque Crystallizes in thin, flexible, six-sided plates or flakes Hardness, between 1 and 2. Easily rubs off on paper, and feels greasy. Specific gravity, 2.2 The most natural home of graphite is metamorphosed (crystallized) sedimentary rocks. Also occurs in veins, and in some igneous rocks. It has many uses, among them being as a lubricant, in making "lead" pencils, crucibles, graphite paint, stove polish, etc Mined in Northern New York, Pennsylvania, Ceylon, etc

Gypsum. — Composition: a compound of lime, sulphur, and oxygen containing water in combination with it. Crystals, usually tabular prismatic (Fig. 8). Colorless or white when pure Transparent to opaque. Hardness, 2, and easily scratched by the finger nail. Specific gravity, 2.3. Three good cleavages crossing at angles of 66° and 114°. Moderately flexible in thin plates. A very clear, crystalline variety is called *selenite;* a fibrous variety, *satin spar*, and a massive or granular variety, *rock gypsum* Gypsum is a common and widespread mineral, especially associated with sedimentary rocks in the form of layers and veins. Its greatest uses are in the manufacture of Plaster of Paris and (when burned) as a retarder for cement.

Halite. — Usually known as "common salt." Composition a simple compound of soda and chlorine. Crystals are usually cubes. Hardness, 2 5. Specific gravity, 2 5. Colorless to white when pure Translucent. Characteristic salty taste. Three good cleavages at right angles and parallel to faces of the cubic crystal Abundant and widespread in sedimentary formations of nearly all ages, sometimes as beds of *rock salt* and sometimes as natural brine or veins Vast quantities occur in the sea and in salt lakes. Halite is very useful, as for example for cooking and preservative purposes, indirectly in glass and soap making, for glazing pottery, and in many ore-smelting and chemical processes

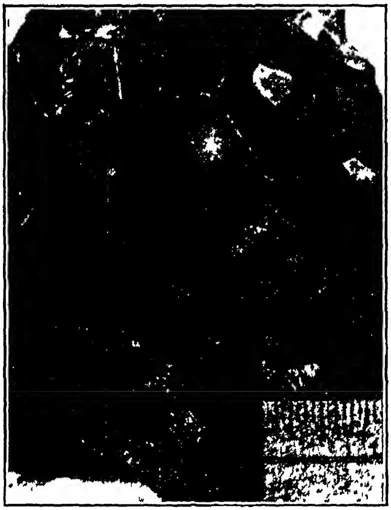

Fig 15

Rounded masses of hematite. (Photo by the author.)

Hematite. — Composition: a simple combination of iron and oxygen Crystallizes in rather complex six-sided forms (Fig 8). Often in rounded masses (Fig 15) Color when crystalline is black with metallic lustre, otherwise it is dull red. Opaque Streak is always red. No cleavage Hardness, about 6. Specific gravity, about 5 (notably above the average) It is very widespread in rocks of all ages, especially in metamorphic and sedimentary rocks, in both beds or layers, and in veins. It is the greatest iron ore, being extensively mined in Minnesota (Fig. 344), Michigan, Wisconsin, and Alabama.

Kaolin. — Commonly called "china clay." Composition: a combination of aluminum, hydrogen, silicon, and oxygen. Seldom crystallizes in small scalelike forms Usually occurs in compact, claylike masses Color, white when pure. Translucent to opaque. Usually feels smooth and plastic. Hardness, over 2 when crystallized; otherwise it is softer Specific gravity, 2 6 Kaolin forms the main body of much clay and shale, and so it is very widespread and abundant. Usually results from decomposition of feldspar. Pure deposits are worked for manufacture of chinaware, pottery, porcelain, etc

Limonite. — Composition a compound of iron and oxygen similar to hematite, but also it contains variable amounts of water in combination. Never crystallizes Color, black to light and dark brown. Opaque. Gives a characteristic yellowish brown streak. Hardness, about 5 Specific gravity, nearly 4. Very common and widespread. Always a product of decomposition of various iron-bearing minerals. It is an iron ore of some importance.

Magnetite. — Composition: a compound of iron and oxygen in different

proportions than in hematite Crystals, usually in regular octahedral forms. Color, black. Opaque Streak, black. Highly magnetic. Hardness, 6. Specific gravity, 5. Widespread as crystals in all kinds of igneous rocks, and in some metamorphic rocks Also occurs as more or less irregular large masses and layers in certain igneous and metamorphic rocks, and in some sands It is an important iron ore, as for example in Northern New York, Norway, and Sweden

Malachite. — This mineral is in almost every way like azurite, except for its color (green), and a slight difference in composition. Translucent to opaque. It is an important ore of copper, as for example in Arizona, New Mexico, Chile, and Mexico.

Micas. — Several species closely related in composition and properties are here included Composition combinations of silicon, oxygen, and aluminum usually with either potash, hydrogen, magnesia, or iron. Crystals are six-sided plates or prisms whose angles are almost 120°. One very fine cleavage at right angles to the prismatic faces, yielding exceedingly thin, elastic sheets Hardness, 2 to 2 5 Specific gravity, 2 7 to 3 Transparent to opaque Hardness, weight, and color vary with the species, most common of which are *muscovite* or *isinglass*, which is colorless in thin sheets where pure; *biotite* which is black, and *phlogopite* which is brown Among the uses of muscovite are as insulating material in electrical apparatus, for stove fronts, as a lubricant, etc.

Olivine. — Often called "chrysolite" Composition· a compound of magnesia, iron, silicon, and oxygen Crystals are usually stout prismatic forms Color, usually yellowish green Transparent to translucent. Hardness, nearly 7 (extra high) Specific gravity, 3 3 No good cleavage. It occurs most commonly in dark, iron-bearing igneous rocks. A clear, green variety, called *peridot*, is used as a gem stone

Opal. — Composition a simple combination of silicon and oxygen containing water in varying amount Never crystallized, probably because of its indefinite composition Hardness, 5 5 to 6 5, varying with varieties. Specific gravity, about 2 Color, variable. Transparent to opaque A few of its varieties are *common opal*, and *wood opal*, usually white to light brown, translucent, and with a greasy lustre; *precious opal*, translucent with a beautiful play of colors and used as a gem; and *hyalite* in colorless, rounded masses

Platinum. — Known as "native platinum" Thickset crystals are very rare. Composition pure platinum. Color, light steel-gray with metallic lustre. Opaque. Hardness, 4.5 (high for a metal). Specific gravity when pure, over 21, making it one of the very few of the heaviest known substances. Very malleable. Found mainly in gravel ("placer") deposits, and rarely in certain igneous rocks, mostly in the Ural Mountains of Russia Used in the electrical industry, for jewelry, and in making certain scientific instruments.

Pyrite. — Commonly called "iron pyrites" Sometimes called "fools' gold" Composition· a simple combination of iron and sulphur Crystals are usually cubes, or thickset twelve-faced forms (Fig 8) Color, light brass-yellow with metallic lustre. Streak, greenish black Opaque. Practically no cleavage Hardness, 6, or greater than that of steel. Specific gravity, about 5 (notably higher than the average) Lighter colored and much harder than chalcopyrite. Common and widespread in rocks of nearly all kinds and

ages, but it especially occurs as veins and lenslike deposits in certain metamorphic rocks, as in Virginia, northern New York, and Spain, where it is mined. Used mostly in the manufacture of sulphuric acid ("oil of vitriol").

Pyroxenes. — A number of species closely related in composition and properties are here included In most respects, particularly in composition, the pyroxenes are much like the amphiboles (above described). Crystals are usually stout to thick-tabular prismatic forms (Fig 8), with the principal faces making angles of approximately 87° and 93° instead of approximately 56° and 124° as in the common amphiboles Two cleavages (not always readily seen) parallel to the prismatic faces cross at angles of 87° and 93° Hardness, 5 to 6, and specific gravity, 3 2 to 3 6, varying with the species. Color, commonly from white through brown to black and sometimes green. Transparent to opaque. The most common species or variety is *augite*, which is dark green, or brown to black. It is a very common constituent of igneous and metamorphic rocks. Clear green *diopside* is sometimes used as a gem stone. One kind of *jade* is a pyroxene.

Quartz. — Composition: a simple compound of silicon and oxygen. Unlike opal, it contains no water. Crystals are very commonly six-sided regular prisms capped by rather steep six-sided or three-sided pyramids (Figs. 6 and 8). Hardness, 7, being much harder than the average mineral. Specific gravity, 2.6 (the average for all minerals) Practically no cleavage, and breaks like glass. Colorless when pure, but varieties exhibit many colors. Transparent to opaque Among the distinctly crystalline varieties are: *rock crystal*, pure and colorless; *amethyst*, purple; *rose quartz*, pink; and *smoky quartz*, dark. Among the very fine grained and non-crystalline varieties are: *Chalcedony*, bluish gray, waxy looking, usually in rounded masses; *carnelian*, red; *prase*, green, *agate*, banded in colors; *flint*, dark and somewhat translucent; and *jasper*, red or brown and opaque.

Next to feldspar, quartz is the most common mineral of the earth's crust. At and near the surface it is the most abundant and widespread It is common in all three great groups of rocks — igneous, sedimentary, and metamorphic. It is a very common vein-filling mineral, often associated with ores. Some of its varieties are used for ornamental and semi-precious stone purposes. It is used in making glass, sandpaper, porcelain, mortar, concrete, and in some ore-smelting processes Sandstone, usually consisting mostly of quartz, is widely used as a building stone.

Serpentine. — Composition: a compound of magnesia, silicon, hydrogen, and oxygen. Color, usually light gray, yellowish green, olive-green, or blackish green, with waxy lustre Translucent to opaque Does not crystallize as such Hardness, variable from 2.5 to 5 Specific gravity, about 2.6. The most common kind of *asbestos* is a fibrous, light-green to white variety of serpentine. Serpentine is always of secondary origin, being a decomposition product of other minerals such as olivine, amphibole, pyroxene, etc. It is common and widely distributed, especially in, and associated with, certain igneous and metamorphic rocks. In large masses it is quarried as a building and decorative stone. Asbestos is much used in making various fire proof materials.

Siderite. — Composition: a combination of iron, carbon, and oxygen. In its crystal form, cleavages, hardness, and effect of warm hydrochloric acid,

it is very much like dolomite Color, light to dark brown Translucent to opaque. Specific gravity, about 4 Usually found in layers in sedimentary formations, or in veins. Used as an iron ore, especially in Great Britain.

Silver. — Known as "native silver" Composition: pure silver. Seldom well crystallized, but usually occurs as irregular masses, plates, and wirelike forms. Color, silver-white with metallic lustre Tarnishes to dark on exposure to air Opaque Hardness, nearly 3 Specific gravity, 10.5 (extra heavy). Malleable Usually occurs in vein deposits along with other metal-bearing minerals.

Sphalerite. — Composition a simple compound of zinc and sulphur. Crystals are usually modified tetrahedrons (Fig 8). Color, yellowish brown, brown, to black, with resinous lustre. Transparent to translucent. Hardness, nearly 4. Specific gravity, 4. Very good cleavages in six directions crossing at angles of 90° and 120°, so that regular twelve-sided cleavage pieces may be broken out of crystals Sphalerite is fairly common and widespread, nearly always occurring in vein deposits Usually associated with other metal-bearing minerals, particularly galena It is the greatest ore of zinc.

Sulphur. — Known as "native sulphur" Crystals are usually combination pyramidal forms with top and bottom truncated (Fig. 8). Color, characteristic sulphur-yellow with resinous lustre Transparent to translucent. Hardness, about 2 Specific gravity, about 2 (unusually low). Cleavages, very poor. Extensive deposits, as in Sicily, have resulted from decomposition of certain sulphur-bearing formations, especially gypsum beds. Some is of volcanic origin Great quantities are used in making sulphuric acid, matches, gunpowder, fireworks, and in vulcanizing and rubber goods bleaching.

Talc. — Often called *steatite* Composition: a compound of magnesia, silicon, oxygen, and hydrogen, much like that of serpentine. Tabular and flakelike crystals are rare. Color white, light gray to greenish. Translucent. Cleavage, excellent in one direction, yielding flexible flakes Feels greasy. Can be sliced with a knife. Hardness, 1 (very soft) Specific gravity, 2.8. Always a secondary product, resulting from decomposition of certain magnesia-rich minerals Used to weight paper, in soap, and as talcum powder. A compact, more or less impure variety, called *soapstone*, is used for making wash tubs, electrical switchboards, blackboards, stove lining, etc

Topaz. — Composition: a compound of aluminum, fluorine, silicon, and oxygen. Crystals are usually flattened prisms capped by pyramids at one end, and abruptly terminated at the other. Colorless when pure, but variously colored by impurities. Transparent to translucent One cleavage only, at right angles to prismatic faces. Hardness, 8 (very hard). Specific gravity, 3.5. Usually found in cavities in igneous rocks. Topaz is a highly prized gem stone.

Tourmaline. — Composition: a complex combination mainly of aluminum and boron with varying amounts of iron, magnesia, manganese, lime, soda, potash, etc. Crystals are prisms with faces in multiples of three capped at each end by pyramids (Fig. 8). Color varies with varying composition, but mostly black or brown. Transparent to opaque Hardness, over 7 (high). Specific gravity, about 3. Practically no cleavage. Commonly occurs in certain kinds of igneous and metamorphic rocks. Some of the transparent, colored varieties are excellent gem stones.

CHAPTER III

MATERIALS OF THE EARTH — ROCKS

Introduction

Definitions. — The solid portion of the earth, or lithosphere, is, as far as known, composed of mineral and rock material. A *rock* may be defined as an aggregate of minerals if we use the term "mineral" in a loose sense to include exceptional material like coal. It is most common by far for a rock to contain two or more mineral species, but in some cases it may consist mainly, or wholly, of one mineral species, such as beds of gypsum, salt, many limestones, and certain iron ores. A rock very often consists of 5 to 10, or more, minerals. Solidity and hardness are not necessary features of rocks, for deposits of loose sand and soft clay are rocks just as truly as the hardest sandstone or granite. A *rock formation* is a more or less extensive constituent of the earth's crust, exhibiting rather characteristic features throughout.

Three Great Groups of Rocks. — Broadly considered, all rocks may be classified in three great groups as follows:

I. *Sedimentary rocks*, comprising all earth materials deposited by water, wind, ice, and organic agencies. Examples, sandstone and limestone.

II. *Igneous rocks*, comprising all earth materials which were once in a molten condition. Examples, lava and granite.

III. *Metamorphic rocks*, comprising all profoundly altered (metamorphosed) sedimentary and igneous rocks. Examples, schist and slate.

General Significance of Rocks. — The science of geology is based largely upon the study of rocks, particularly in regard to their origin and history; the forces of nature which affect them; and the events of earth history which they record. It is, therefore, important that the student of geology should early gain at least an elementary knowledge of the more common kinds of rocks. Only by a knowledge of the nature of the materials of the lithosphere (mostly rocks) can the action of geological processes upon them be rightly understood. To this end the student should

supplement his reading with study of specimens in the laboratory, and of actual rock exposures in the field, as far as that may be feasible.

Sedimentary Rocks

General Characteristics. — Rock and mineral matter of any kind carried by water, wind, or ice becomes *sediment*, which, in the course of time, is deposited as such. Most sedimentary rocks by far originate as sediments. ~~One of the most~~ common characteristics of such sedimentary rocks is their division into layers, i.e. their *stratification* (Fig. 16). By throwing a quantity of loose rock material, the fragments of which range from very fine to coarse, into standing water, the coarsest material would settle first, and upon it successively finer and finer material. There would be a gradation from the coarsest material at the bottom to the finest at the top. By repeating the process a similar *layer* (or *bed*) would accumulate on top of the first, and the two layers would be separated rather sharply by a *stratification* or *bedding surface.* In water with a current there would be a tendency toward horizontal as well as vertical gradation of the sediment in each layer or bed due to the sorting power of the running water. The term *stratum* (plural, *strata*), strictly speaking, applies to a collection of successive beds or layers of the same sort of rock material, but is very often used in the same sense as *bed* or *layer*. It should be borne in mind that some sedimentary rocks show little or no sign of stratification, as for example in the case of many glacial deposits. Wind deposits are often more or less crudely stratified.

Another common characteristic of many sedimentary rocks is the rounded nature of the fragments and particles which compose them. This is due to the fact that any sharp angles of rock and mineral fragments tend to be worn away by abrasion during transportation by water, wind, or glaciers. This feature stands in sharp contrast with that of the typical igneous rocks which are masses of more or less angular minerals (or crystals).

Sedimentary rocks often contain *fossils* (Fig. 2), that is, remains or impressions of animals and plants, while igneous rocks by their very nature almost never do.

Where Sediments are Deposited. — The ~~greatest~~ theatre of sedimentation is the sea. The general tendency is, and has been

for long ages, for the land waste, resulting from disintegration and decay of rocks, to be carried into the sea, very largely by rivers. Most of this sediment, amounting to vast quantities each year, is deposited in the shallow water relatively near the land, that is, within 100 to 200 miles of the shore. Shells and remains of various animals and plants, as well as volcanic materials (especially dust), accumulate over vast areas of the sea floor.

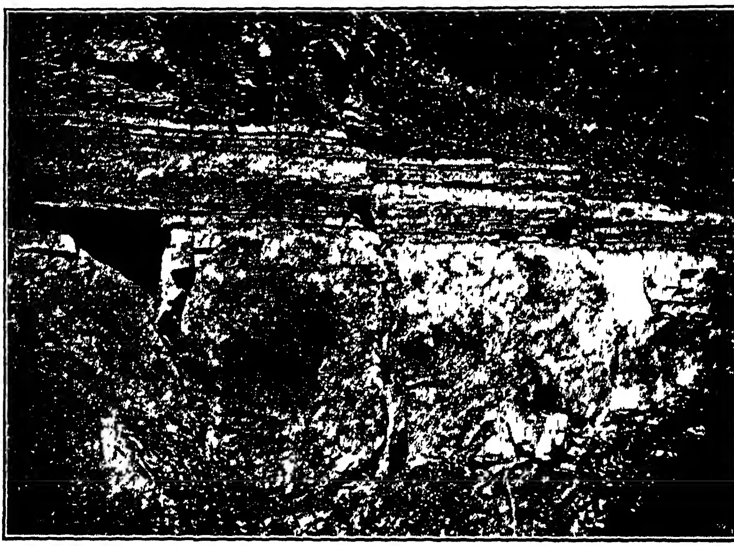

Fig. 16

An outcrop of sandstone showing a thick bed below and thin beds above. Near Johnstown, New York. (Photo by the author)

Large quantities of material worn from the shores by wave action are also deposited in the sea.

Most lake bottoms receive sediments both derived by wave action and carried in by streams. Mineral matter in solution, such as salt and gypsum, may also be precipitated during evaporation of lake water.

More or less deposition of the tremendous amount of sediment carried by streams takes place along the stream courses, particularly on their flood-plains, or where streams emerging from mountains flow out into deserts and dry away.

Vegetable matter, which in many places may be changed into coal, accumulates in swamps, bogs, and some lakes.

Various types of sediments are deposited directly upon the land. Thus piles of rock fragments derived from cliffs often accumulate at their bases; wind, especially in desert regions, transports and deposits great quantities of dust and sand; mineral-charged waters (springs) emerging from the earth deposit their

Fig. 17

A specimen of conglomerate (Photo by the author.)

mineral matter at the surface; and glaciers transport and deposit large amounts of rock waste directly upon the land.

How Sediments are Consolidated. — Most sedimentary rocks are now consolidated into relatively hard rocks, but at the time of their deposition they were mostly loose, incoherent masses. Thus the familiar rock known as sandstone was once loose sand, and shale was formerly soft mud. What causes the consolidation of sediments? One important factor is *weight* or *downward pressure*. Where strata pile up to thicknesses of many hundreds, or

even thousands, of feet as they commonly do, the weight or downward pressure of the overlying masses tends to squeeze together the fragments and particles of the lower masses of the pile, causing them to consolidate, perhaps by adhesion and cohesion.

Cementation is another important cause of consolidation of sediments. Waters penetrating the earth's crust carry various minerals in solution, and at considerable depths such minerals are deposited in the spaces of the loose sediment, causing the whole mass to be tightly bound together.

Consolidation may also be effected by *heat*. The source of the heat may be bodies of molten material which rise locally into masses of strata, or it may be the general interior heat of the earth where the bottom portions of thick piles of strata are far enough down to become appreciably affected.

Mention may be made also of the influence of *lateral pressure* in the consolidation of sediments. Such a pressure may be exerted upon a great body of strata, causing it to be crumpled and raised into a mountain range as explained in Chapter XIII.

Kinds of Sedimentary Rocks. — The more common kinds of sedimentary rocks may be classified in a general way as follows:

Principal Kinds of Sedimentary Rocks

1. Mechanical or fragmental origin.	Sands and sandstones. Gravels and conglomerates. Clays and shales. Loess. Talus and breccias.
2. Chemical origin.	Salt and gypsum. Some limestones. Travertine and siliceous sinter. Bog iron-ore.
3. Organic origin.	Most limestones, including chalk. Diatomaceous earth Peat, lignite, and coal.

Sedimentary rocks of mechanical origin. — The sedimentary rocks classified in this category are of mechanical origin, and they consist largely or wholly of fragments of preëxisting rocks carried along and deposited by water, wind, or ice. They are known as *clastic rocks*.

Sands are incoherent masses of fine, more or less rounded grains of mineral or rock fragments, usually consisting mainly of quartz. The grains are not more than a few millimeters in diameter.

Sandstones are consolidated sands of varying degrees of hardness. The grains of sand are generally held together by a cement such as lime, oxide of iron, or oxide of silicon (silica), etc Sandstones are generally stratified in layers varying from thin to thick

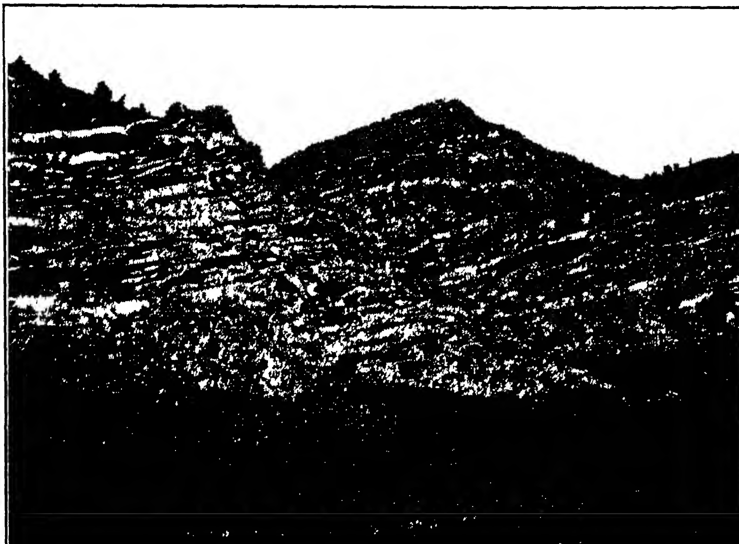

Fig 18

A large exposure of sandstone and conglomerate. Weber Canyon, Utah (Photo by the author)

(Fig. 16). They vary greatly in color according to the nature of the fragments, cementing material, and impurities which they contain. They are most often white, gray, brown, or red. Sandstones are usually very porous because of the numerous, relatively large spaces between the grains of the rock. There are many more or less impure varieties of sandstone, as for examples *calcareous sandstone*, containing much lime; *micaceous sandstone*, containing many flakes of mica; *argillaceous sandstone*, rich in clay; and *arkosic sandstone*, rich in fragments of feldspar.

Gravels are incoherent masses of more or less rounded pebbles of any kind of rock ranging in size from a few millimeters to boulders a foot or more in diameter. The most common pebbles are of quartz, not only because this mineral is so abundant, but also because it is so hard that the rolling and rubbing action of water, wind, or ice often only rounds off pebbles of it, while softer minerals and rocks are reduced to fine materials.

Conglomerates are masses of gravel cemented together (Fig. 17). They are usually much more crudely stratified than sandstones because of the conditions under which they are deposited. They

Fig. 19
Steeply inclined shale beds Sunland, Los Angeles, California. (Photo by the author.)

are given various names according to the prevailing kinds of pebbles in them, as *quartz conglomerate*, *granite conglomerate*, *limestone conglomerate*, etc.

Clays consist of very finely divided, decomposed rock and mineral matter of various kinds, but usually mostly of kaolin. They are plastic when moist. *Muds* are made up of very finely divided, little decomposed or fresh rock and mineral fragments of various kinds. They show little or no plasticity when moist. *Shales* are consolidated clays and muds. Clays, muds, and shales commonly vary in color from white through gray to black, and from bluish-gray or yellow through brown to red, the latter colors usually being due to the presence of an iron compound of

some kind. Dark gray to black clays and shales usually owe their color to the presence of considerable decomposing organic matter, as for example *carbonaceous shale.* A limy clay is usually called *marl.* There are also *sandy shales,* containing considerable sandy material, and *calcareous shales,* containing more or less limy material. Shales and clays are usually well stratified, often in

Fig 20
A specimen of shell limestone many millions of years old. (Photo by the author)

thin layers (Fig. 19). Thin-bedded shales may be readily split into thin plates parallel to the stratification.

Loess is a very fine grained, usually buff colored sandy, often limy, clay, mainly of wind-blown origin.

Talus is a mass of more or less angular, loose fragments of rock of any kind that accumulates at the base of a cliff or steep slope (Fig. 47). *Breccias* are masses of more or less angular rock fragments which have been cemented together.

Sedimentary rocks of chemical origin. — In this category are

included all sedimentary rocks which have been formed by deposition (or precipitation) of mineral matter from solution.

Salt and *gypsum* are precipitated from salt lakes and lagoons which are subject to excessive evaporation, that is, where evaporation balances or exceeds inflow of water. The tendency is thus for the mineral matter to accumulate in solution until the point of

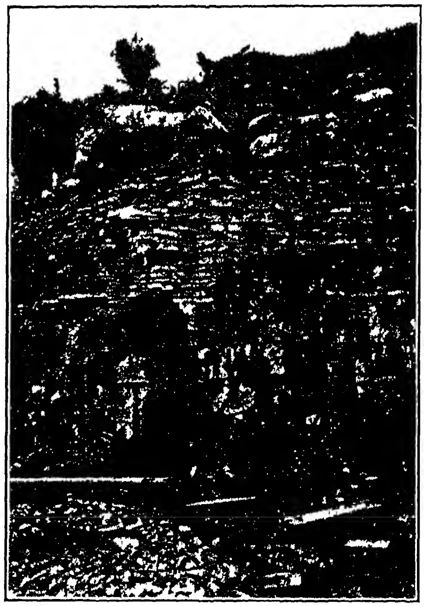

Fig. 21
An outcrop of limestone of Ordovician age. Glacial boulders on top. (Photo by the author)

saturation is reached, after which precipitation results. If both salt and gypsum are in solution the gypsum is deposited first because it is less soluble than the salt. Extensive deposits of both of these minerals exist in many regions, and they are usually well stratified. When pure they are white, but they are often variously colored by impurities.

Where lime is in solution in lakes or lagoons, excessive evaporation may lead to its deposition, thus forming limestone. Such

limestone is, however, far less common than that of organic origin described beyond.

Travertine and *siliceous sinter* are more or less porous, usually white, spring deposits, being especially conspicuous around the mouths of hot springs. They are both remarkably well developed in Yellowstone Park, the former at Mammoth Hot Springs, and the latter around the geysers. Travertine consists of limy material which bubbles when touched with hydrochloric acid, and siliceous sinter consists of silica, that is, a compound of silicon and oxygen which is not affected by the acid.

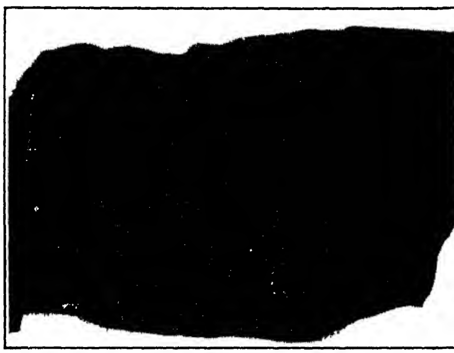

Fig. 22
Ancient (Triassic) ripple-marked sandstone.
(Photo by the author.)

Bog iron-ore precipitates on the floors of certain bogs or lakes when an iron compound in solution in the water becomes oxidized, and therefore insoluble.

Sedimentary rocks of organic origin. — Most *limestones* consist of the limy shells, or fragments of shells, or other limy remains of animals and plants, mostly of animals. In many cases the organic remains, or at least fragments of them, are obvious to the naked eye (Fig. 20). In some cases such material can be made out only under a hand lens or microscope. In still other cases the limy organic remains either have been so thoroughly ground up (e.g. by waves on coral beaches), or so completely altered by crystallization, that the original organic structures are wholly obscured. Most of the great, very extensive limestone formations

have formed on the sea floor by accumulation of limy shells, etc. Limestones are usually well stratified (Fig. 21).

Chalk is a very fine grained, soft limestone with an earthy texture. It is usually white to light gray. Much chalk consists of the tiny shells of single-celled animals known as Foraminifera. Limestones are often impure due to a mixture with more or less sandy or clayey material, etc., and become *sandy limestones, clayey* (or *argillaceous*) *limestones,* etc. *Shell marl* is clayey mate-

Fig. 23

Mud cracks in a desert, near Cedar City, Utah. (Photo by the author.)

rial rich in limy shells or fragments of shells. All rocks here described under the category of limestones bubble when treated with ordinary acid. They are usually well stratified.

Diatomaceous earth is soft, very fine grained, usually white or gray earthy material composed mainly or wholly of the siliceous shells or secretions of minute, single-celled plants called Diatoms. It is usually well stratified, often in exceedingly thin layers when it is sometimes called diatomaceous shale (Fig. 19). It looks much like chalk, but acid does not affect it.

Peat, lignite, and *coal* all represent accumulations of beds of vegetable matter, usually under swamp conditions, which have been more or less decomposed (or carbonized) Vegetable matter of this kind, when only slightly altered, is called peat; when it is somewhat more decomposed it is called lignite (an imperfect coal); and when it is very much changed under conditions of burial in the

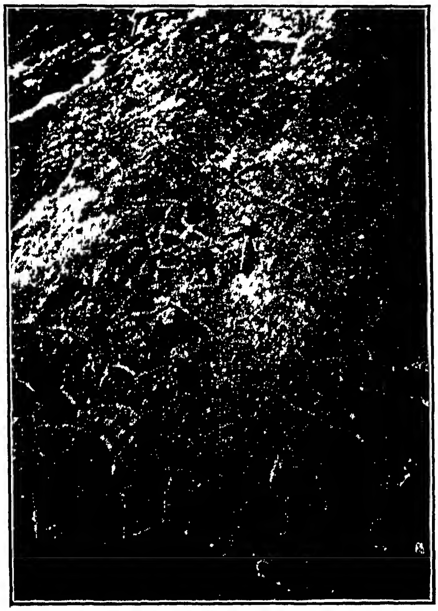

Fig 24

Filled mud cracks many millions of years old on sandstone Glacier Park, Montana. (Photo by the author)

earth, so that the percentage of carbon is relatively high, it is called coal, including both bituminous and anthracite coal. Coal is more or less well stratified, and it usually forms beds between beds of shale or sandstone.

Special Features of Strata. — *Ripple marks*. These are small parallel ridges, seldom more than a few inches high, formed by the rippling action of either water or wind on certain incoherent sediments, especially sands and sandy materials in general. They

are particularly characteristic of the action of waves in shallow water. A ripple-marked surface may be hardened enough to be deeply buried under other strata, and later exposed by removal of the overlying strata by a natural process (erosion). Figure 22 shows ripple marks of this kind millions of years old. Ripple marks are also made by wind action on wind-blown deposits, particularly on sand dunes (Fig. 231).

Fig 25

Cross-bedded sandstone of Triassic age Near Kanab, Utah. (Photo by D. W. Johnson)

wet

Mud cracks. When soft ~~mud~~ or sandy mud is left exposed to the air after withdrawal of high water, the material dries and cracks into a network of fissures (Fig. 23). Flood plains of rivers and desert basins, with their alternating wet and dry surfaces, are often very favorable for their development. During dry weather such a cracked surface hardens, and the fissures may either be filled with wind-blown dust or sand, or the next flood may first fill the cracks, and then the whole surface with coarser sediment. Thus a mud-cracked surface may, in the course of time, be deeply buried below the surface, and later exposed by wearing

away of the land. Figure 24 shows part of such a re-exposed mud-cracked surface tens of millions of years old.

Cross-bedding. This is irregular bedding at various angles to the general planes of stratification of a formation (Fig. 25). It is caused by the action of tides or water or wind currents varying

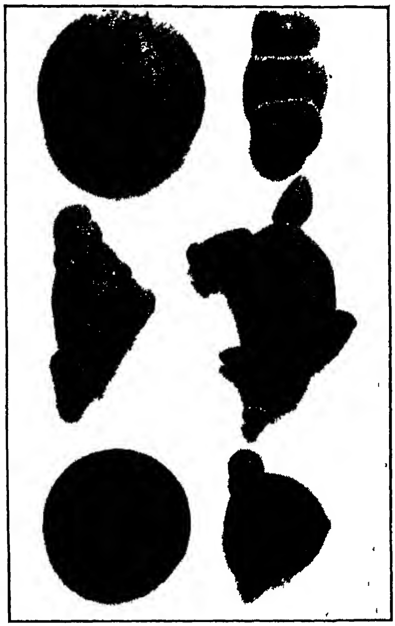

Fig 26

Concretions from clay beds of the Connecticut Valley, Massachusetts. One-half natural size. (Photo by the author)

notably in force or direction. Rapid, shifting currents in shallow water of rivers, lakes, and even the sea favor its development. Wind-blown deposits are also often cross-bedded because of the shifting conditions of deposition.

Fossils. Stratified rocks very often contain remains or impressions of animals and plants of former geologic ages. Sediments which were deposited in the sea are, as a rule, richest in such

fossils (Fig. 2). Lake and river deposits also often contain fossils, and sediments accumulated on land sometimes do (Fig. 5). Even occasional tracks of land and water animals of millions of years ago are wonderfully preserved.

Concretions or nodules. These are rounded or irregular masses of material differing in kind and rather sharply separated from the beds or strata in which they occur, and harder than the latter. They are found in a great variety of shapes, sometimes suggesting

Fig 27
Concretions in Tertiary sandstone. Los Angeles, California. (Photo by the author)

fossil forms. Some small ones are shown in Fig. 26. They range in diameter from less than an inch to a number of feet or yards. They are not pebbles or boulders deposited along with the sediments which contain them as proved by the fact that stratification surfaces often pass right through them. They are segregations, possibly aided by some crystallization, of certain materials, often around some object like a shell or leaf, formed either during or after the consolidation of the sediment. Their precise mode of origin is, however, not known.

Igneous Rocks

General Characteristics. — Igneous rocks are usually massive as compared to the generally stratified character of the sedimen-

tary rocks. In some places, as with lava flows (Fig. 257), igneou rocks may be piled up in layers, but such rocks can, by their othe characteristics, be told from stratified rocks. Among such othe characteristics of igneous rocks are the general uniformity o appearance of masses or layers for considerable distances, botl vertically and horizontally; the usual angular, instead of rounded shapes of many, or all, of the mineral constituents; the peculia

Fig 28
A specimen of granite (Photo by the author)

texture, especially the interlocking of the minerals; their mode o occurrence, especially where they cut across other rocks; th effects of their heat upon adjacent rocks; and their almost utte lack of fossils.

Minerals and Textures of Igneous Rocks. — When th temperature of a mass of molten material, called *magma,* slowl lowers, a time finally comes when crystals of minerals begin t grow, and the process continues until the whole mass become

solid. With more rapid cooling, some of the mass may not crystallize, and, under conditions of very rapid cooling, the magma may solidify with little or no crystallization. Among the many minerals known to crystallize from magmas, a few only are very common, such as the feldspars, quartz, the amphiboles, the pyroxenes, the micas, olivine, and magnetite.

When a magma cools very slowly and uniformly within the earth's crust, the whole mass becomes crystalline with mineral

Fig 29
A specimen of lava showing a porphyritic texture (Photo by the author)

grains readily determinable and of approximately uniform size, though seldom with well-defined crystal faces. This is called a *granitoid texture* (Fig. 28). When the rock contains many mineral grains too small to be made out by the naked eye, it is said to have a *compact* (or *felsitic*) *texture*. Such a rock may be partly uncrystallized. Igneous rocks with relatively large crystals (often with good crystal outlines) embedded in a fine grained or glassy ground mass are said to have a *porphyritic texture* (Fig. 29). Such a texture indicates two distinct stages of crystallization. Very

rapid cooling may result in the solidification of a magma with little or no crystallization. Such a rock possesses a *glassy texture* (Fig. 30). The term *fragmental texture* may be applied to an accumulation (loose or consolidated) of fragments of igneous rocks which have been explosively ejected from volcanoes, such as *volcanic dust* (or *tuff*) and coarser materials (or *volcanic breccia*).

Plutonic and Volcanic Igneous Rocks. — In regard to modes of occurrence of igneous rocks, there are two main types, the

Fig. 30
A specimen of obsidian (volcanic glass).
(Photo by the author.)

plutonic or *intrusive* and the *volcanic* or *extrusive*. The former type results from cooling of magma which has been forced into the crust of the earth, but not to its surface, for example granite. Such rock is now visible only because of removal of the overlying material by natural agencies. The latter (volcanic) type results either from solidification of magma which pours out on the earth's surface (e.g. lava flows), or from accumulation of igneous rock fragments which are thrown out by explosive action of volcanoes

(Fig. 277). The modes of occurrence of igneous rocks are considered toward the end of Chapter VI.

Kinds of Igneous Rocks. — The principal kinds of igneous rocks may be classified in a general way on the basis of essential mineral content and texture. In the study of the table presented herewith, it must be clearly understood not only that various accessory minerals are not listed, but also that adjacent types in the classification are not always sharply defined because many intermediate (gradational) types are known

Principal Kinds of Igneous Rocks

		Orthoclase and quartz, etc	*Orthoclase, but no quartz, etc*	*Plagioclase and biotite or hornblende, etc*	*Plagioclase and pyroxene, etc*	*No feldspar Biotite, hornblende, or pyroxene, etc*
Mainly Volcanic	*Glassy or Fragmental*	Rhyolite obsidian, tuff, breccia, etc	Trachyte obsidian, tuff, breccia, etc	Andesite obsidian, tuff, breccia, etc	Basalt obsidian, tuff, breccia, etc	Limburgite tuff, breccia, etc
	Felsitic	Rhyolite	Trachyte	Andesite	Basalt	Limburgite
Intermediate	*Porphyritic*	Rhyo and Gra porphyries	Trach and Sy porphyries	And and Dior porphyries	Bas and Gab porphyries	Lim and Per porphyries.
Mainly Plutonic	*Granitoid*	Granite	Syenite	Diorite	Gabbro	Peridotite.
		Granite family	Syenite family	Diorite family	Gabbro family.	Peridotite family
		Usually light-colored		Usually dark to black		

Having a knowledge of the common minerals and textures involved in the above classification, the student should carefully examine specimens of most of the types of igneous rocks listed. Such practical work may well take the place of printed descriptions of the various types.

Metamorphic Rocks

Meaning of Metamorphism. — *Metamorphism* means any change in mineral composition, structure, or texture of an igneous or a sedimentary rock whereby the original rock character is

notably altered. In many cases the products of metamorphic action look utterly different from the rocks from which they were derived, while in many other cases some of the original features are retained. Simple consolidation of loose sediment, like that of clay into shale, is not regarded as a metamorphic process. Disintegration and decay of rocks under the action of the weather (atmospheric agencies) are, however, processes of metamorphism in the broad sense of the term.

Sedimentary rocks which have been thoroughly metamorphosed "are much harder, denser, more crystalline, and the fossils, and perhaps even the marks of stratification, have been

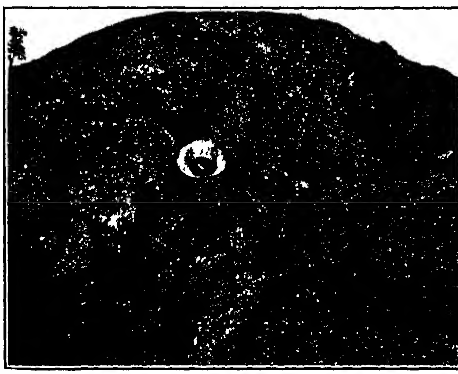

Fig 31
A ledge of gabbro St. Lawrence County, New York (Photo by the author)

more or less completely obliterated. As to the igneous rocks, the particular features which distinguish them may disappear, and they may assume a banded appearance and cleavage which resemble those of sedimentary kinds" (Pirsson). Without careful field study, it is sometimes impossible to tell whether a given metamorphic rock was originally igneous or sedimentary.

Agencies of Metamorphism. — How do igneous and sedimentary rocks become metamorphosed? Brief mention will now be made of the principal agencies of metamorphism. *Liquids*, particularly water on and in the earth, are often effective agents of alteration of rock material by dissolving it, after which it may crystallize in new mineral combinations.

Various *gases* and *vapors*, especially those which escape from molten masses into surrounding rocks, often effect important chemical changes and rearrangements of mineral matter in rocks.

Heat is an important metamorphic agency. By it liquids and gases are rendered much more active. It helps to alter the composition of many minerals, and to bring into existence new ones. A sedimentary rock mass may be metamorphosed by heat along the border of a molten mass which is intrusive into the sediment A rock mass may be heated not only by a hot, igneous body, but also by deep burial within the generally heated crust of the earth.

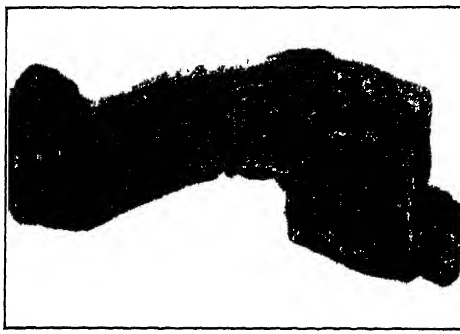

Fig 32
A specimen of crumpled schist. (Photo by the author)

Some heat may also result from disturbances of the crust due to shrinkage of the earth.

Lateral pressure is a very important agency of metamorphism of both igneous and sedimentary rocks. We shall learn in another chapter that the crust of the earth is, and has been, in many places subjected to tremendous stresses and compressive forces due to earth shrinkage, causing rocks to be bent, mashed, sheared, fractured, and often locally crumpled into mountain ranges. Mineral grains or rock fragments may thus be crushed or flattened; mineral rearrangement may take place; and the rock structure and texture may be greatly changed.

Downward pressure exerted upon deeply buried rocks, particularly sediments, aided by the heat of the earth's interior, and often

by water or other liquid, is probably another important factor in the transformation of rocks.

In some cases the agencies mentioned may operate only very locally, causing *local metamorphism*, while in other cases they may bring about great changes over extensive areas, causing *regional metamorphism*.

Minerals and Structures of Metamorphic Rocks. — Relatively few common minerals make up the great bulk of metamorphic rocks. Chief among them are quartz, the feldspars, the micas, the amphiboles, the pyroxenes, calcite, and dolomite. Most igneous and metamorphic rocks are similar in regard to their

Fig 33
An outcrop of schist. Hoosac Mountain, Massachusetts (Photo by the author.)

distinctly crystalline appearance, but they are unlike in that the metamorphic rocks usually have a parallel structure or arrangement of mineral grains, often resembling stratification. In some cases this structure is parallel to original bedding of strata, but more often it is not. It should be kept in mind that not all igneous and metamorphic rocks are crystalline, and that not all metamorphic rocks possess a parallel structure. Such cases are, however, relatively exceptional.

Foliation is the arrangement of the mineral constituents of a metamorphic rock with their long axes more or less parallel, thus causing the rock to have a parallel structure. It is a secondary structure, that is, it is developed in the original rock mainly by

pressure after the rock was formed as such. A rock possessing foliation is called a *foliate.* Well-developed foliation causes *cleavage,* that is, a tendency for the rock to split in layers parallel to the foliation. Well-developed foliation in a very fine grained, not obviously crystalline, rock is called *slaty cleavage,* well illustrated by common roofing slate. A highly crystalline rock with an excellent foliation (or cleavage) is called a *schist* (Fig. 33).

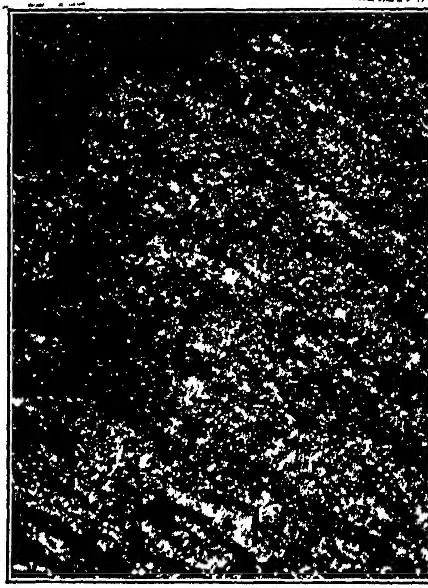

Fig. 34

A specimen of granite gneiss. (Photo by the author.)

A rock with crudely developed foliation is called a *gneiss* (Fig. 34). The term *gneissoid* may be applied to an igneous rock in which a crudely developed foliated structure is developed during the consolidation of the magma.

Kinds of Metamorphic Rocks. — The metamorphic rocks are, ~~on account of their~~ complicated nature and origin, difficult, if not ~~impossible, to~~ classify satisfactorily. The following table is a grouping of the most important types of metamorphic rocks on the basis of their origin and general structure.

Principal Kinds of Metamorphic Rocks

I. Metamorphosed Igneous Rocks	1. Foliates.	*a.* Granite gneiss, diorite gneiss, etc. *b* Gneissoid granite, gneissoid diorite, etc. *c.* Some hornblende schist and gneiss (or amphibolite). *d.* Some slate.
	2 Non-foliates.	Serpentine, soapstone, altered lavas, etc.
II. Metamorphosed Sedimentary Rocks	1. Foliates.	*a.* Mica schist and gneiss. *b.* Hornblende schist and gneiss (or amphibolite). *c* Quartz schist. *d.* Conglomerate gneiss and schist. *e.* Marble gneiss and schist. *f.* Most slate.
	2. Non-foliates	*a.* Quartzite. *b.* Marble. *c.* Anthracite. *d.* Certain contact metamorphic rocks.

III. Various Gneisses and Schists — some formed by magmatic injection, and some of unknown origin.

IV. Weathered Rocks, Residual Soils, etc.

With some brief explanations, rock types listed in the above table may be readily understood. Igneous rocks which have their foliation impressed upon them after complete solidification of the magma may be named *granite gneiss* or *schist*, etc., according to the kind of igneous rock involved. Those whose foliation develops during the process of solidification of the magma may be named *gneissoid granite, gneissoid diorite,* etc., according to the kind of rock. Some *hornblende schist* (or *amphibolite*) is simple foliated hornblende-rich igneous rock. Some slate is igneous rock with a typical slaty cleavage. Among the non-foliated, igneous, metamorphic rocks, *serpentine* and *soapstone* are chemically highly altered gabbro, peridotite, etc., and some lavas have also been notably altered chemically.

Many names have been applied to various foliated sedimentary rocks. Thus *mica* or *hornblende schist and gneiss* are thoroughly crystalline foliates rich in the particular minerals mentioned. Both of these minerals may occur in the same rock, usually also with feldspar. They are mainly foliated shales. *Quartz schist* is foliated, impure sandstone often containing mica. *Conglomerate gneiss* is simply foliated conglomerate, and *marble gneiss* is simply foliated impure limestone. Most *slate* is foliated shale with

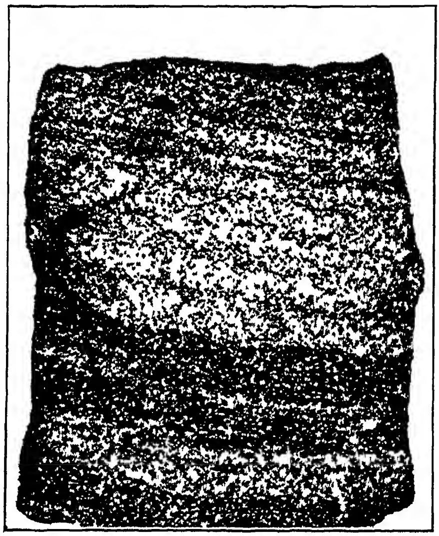

Fig 35
A specimen of gabbro-granite injection gneiss. (Photo by the author.)

highly developed slaty cleavage but with very little crystallization. Among the non-foliated metamorphosed sedimentary rocks are *quartzite*, a rather massive rock derived from rather pure sandstone; *marble*, derived from limestone; *anthracite*, which is altered bituminous coal; and certain metamorphic rocks produced by the heat of magma near its contact with sedimentary rocks.

Some of the various gneisses and schists mentioned in the third subdivision of the above table are formed by more or less intimate penetration or injection of any kind of rock by magma.

They may be designated by such terms as *quartzite-gabbro injection gneiss*, or *schist, gabbro-granite injection gneiss* or *schist*, etc., according to the rocks involved. Various other gneisses and schists in this third subdivision may not be definitely known in regard to

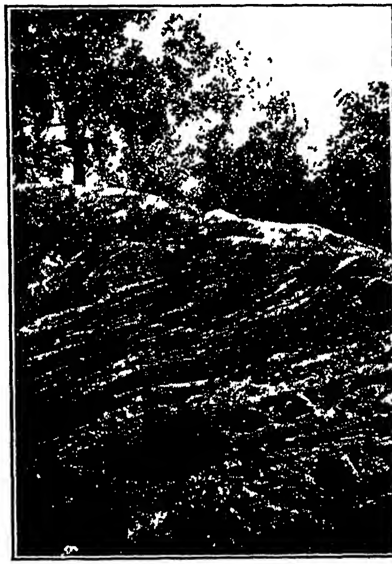

Fig 36

An outcrop of banded gneiss Clinton County, New York (Photo by the author.)

their igneous or sedimentary origin. They may be designated by rather non-commital terms such as *granitic gneiss* or *schist, dioritic gneiss* or *schist*, etc., according to their mineral content.

The weathered rocks are simply products of rock decay and disintegration.

CHAPTER IV

ROCK WEATHERING

General Significance of Weathering

All the materials of the outer or crustal portion of the earth are subject to ceaseless change. Under the action of the weather and other more or less closely related agencies, even the hardest and most resistant rocks crumble or decay in the course of time (Figs. 37, 45, 48, and 52). Weathering effects are, as a rule, scarcely noticeable during the ordinary span of a human life, but, during the eons of geological time, weathering processes have been relentlessly at work upon the surface and near-surface portions of the earth, causing such tremendous quantities of rock material to be broken up and decomposed that the lands have been profoundly affected. In fact, most of the materials by far which make up the vast bodies of sedimentary rocks are products of rock weathering which have been transported from their places of origin.

In its earlier application, the term weathering usually included only the direct action of the weather or atmospheric agencies upon rocks and minerals, causing them to break up or decay. According to present usage, *weathering* comprises all processes, such as mechanical action of temperature changes, freezing of water, organisms, rain water, and lightning, and the chemical action of atmospheric gases, water, and organisms, whereby rocks at and near the earth's surface break up, decay, or crumble. Even as thus broadly defined, the direct action of the weather is the most important factor in the complex set of processes called weathering.

Rate of Weathering

The rate of weathering depends upon the nature of the rocks, and the kinds and conditions of the weathering agents which operate upon them. It is a matter of common knowledge that many stone buildings and monuments show marked effects of

weathering. An excellent case in point is Westminster Abbey in London which was built of weak, rather porous stone in the thirteenth century. Many of its outer stones are badly weathered, some of its ornamental, carved parts having been reduced to shapeless forms. Many of the exterior carvings of soft limestone of the Louvre in Paris are also badly weathered. Inscriptions on many tombstones and monuments only one or two centuries old are often nearly, or quite, illegible, due to weathering. Weathering is, however, much less rapid in the case of hard, resistant rocks. Thus, even the polished surface of a very resistant rock, like granite or quartzite, may be preserved for many years although exposed to very vigorous and changeable weather conditions. There are ways of estimating that many thousands of years are required for enough weathering to develop a soil a few feet thick from (and resting upon) a hard rock like granite (Fig. 52).

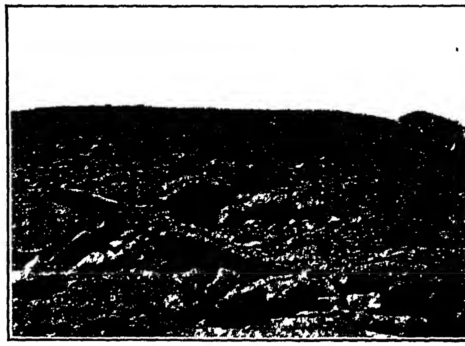

Fig 37

Granite broken up by frost action Summit of Long's Peak, Colorado, at an altitude of 14,255 feet. (Photo by the author.)

Mechanical Weathering

Broadly considered, there are two general processes of weathering — one mechanical, and the other chemical. In *mechanical weathering* the rock breaks up or crumbles with little or no change in the composition of the material. It is essentially a physical process of disintegration. In *chemical weathering* the composition of the rock or mineral matter is more or less altered during its breaking up. It is essentially a process of decay or decomposition. Although the processes of disintegration and decomposition may be thus distinguished, nevertheless the two processes very commonly operate together in nature, now one and now the other being predominant.

Freezing and Thawing of Water. — Not only in cold countries, but also in the mountains of regions with generally mild climates, alternate freezing and thawing of water is an effective agency in breaking up rocks, especially where soils are absent or very thin. Most relatively hard rocks contain not only numerous natural fractures called joints (see page 118) which separate them into more or less distinct blocks, but also small crevices, fissures, and

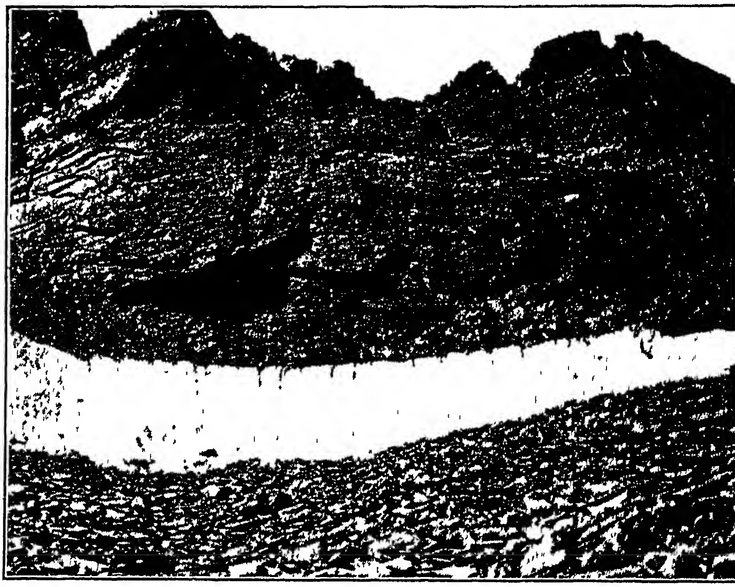

Fig 38
Exfoliation of granite on the north face of Long's Peak, Colorado. (Photo by the author)

pores. Surface water may fill such openings. Such water expands about one-tenth of its volume on freezing, and exerts the tremendous pressure of over 2000 pounds per square inch upon the walls of the opening or fissure. If the rock is favorably situated, the pressure will widen the opening a little. Repeated freezing and thawing of water which finds its way into such openings finally causes even the hardest rocks to be mechanically broken up into smaller and smaller fragments. Jointed rocks situated on the faces of cliffs and steep slopes are especially subject to such action,

as are also jointed or fissured boulders, pebbles, and even soil particles.

Temperature Changes. — Changes of temperature, producing expansion and contraction of rocks and minerals, are very important agents of mechanical weathering. The principle involved is that all parts of a rock mass do not expand and contract at equal rates when subjected to temperature changes, and so stresses are set up which cause the rock to break. Such effects are most conspicuous on high mountains (Fig. 38), and on deserts not only because rocks are there generally barren, but also because a daily range of 50 to over 100 degrees in temperature is frequent. In many deserts the outer portions of rock ledges and boulders exposed to the rays of the sun are heated to temperatures of 100° to 150° during the day and, therefore, expand, but during the night the temperature commonly falls 50° to 100°, and the outer portions of the same rocks contract notably. Such rapid changes, causing repeated strains of this kind between the outer and inner portions of the rocks, finally cause the latter to break just as cold glass breaks when plunged into hot water. Most rocks consist of two or more kinds of minerals, each of which expands at a different rate, and so additional, minor stresses and strains are set up, tending to pull apart the minerals and disrupt the rocks.

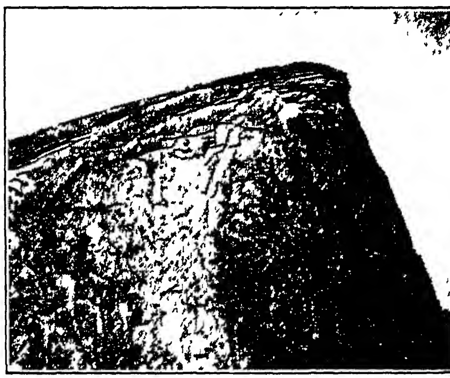

Fig 39

Exfoliation of granite at the top of Half Dome, Yosemite Park, California. (Photo by the author.)

When, due to rapid temperature changes, the outer portions or surface layers of rocks peel, or scale, off in slabs or sheets, the process is called *exfoliation.* Rock surfaces tend to round off by this process, excellent examples being Stone Mountain in Georgia (Fig. 40), and many of the high mountains of the central and

southern Sierra Nevada Range in California (Fig. 316). The principle of exfoliation is much like that which causes so-called "spalling" of stones in buildings during fires, particularly when cold water is thrown on the hot surfaces. Spalling is wonderfully illustrated in the ruins of the famous Rheims Cathedral.

Mechanical Action of Organisms. — Both directly and indirectly, plants and animals accomplish considerable work of rock

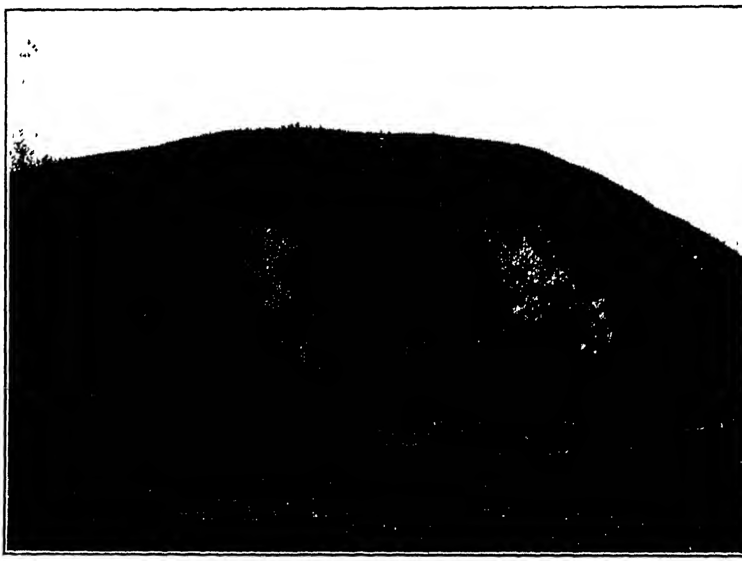

Fig 40
Stone Mountain, Georgia, rounded off by exfoliation.
(After Hillers, U. S. Geological Survey.)

disintegration. Roots and trunks of plants, especially of the higher forms, like trees, insert themselves in rock crevices and cracks, and as they grow they exert a powerful force, often sufficient to wedge the rock apart. Repetitions of this wedgework process often cause the rock to be broken into small fragments. Various rootless plants, such as lichens, attach themselves to rock surfaces and loosen off rock particles as they grow.

Indirect actions are the overturning of trees, causing relatively fresh rock materials to be brought to the surface and better ex-

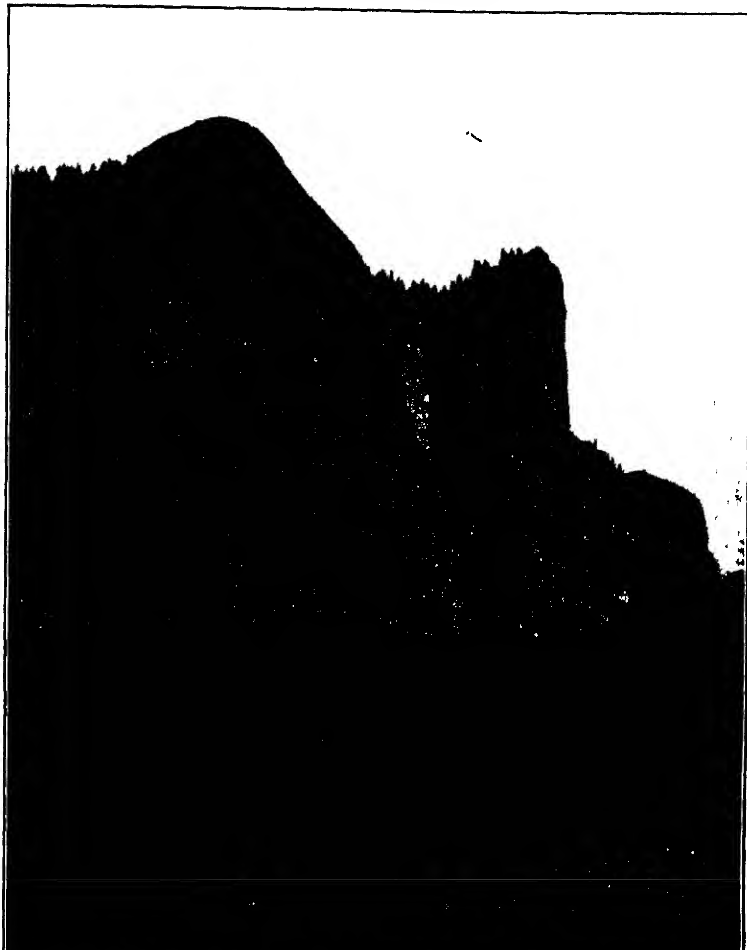

Fig 41

The Royal Arches, Washington Column, and Basket Dome in Yosemite Valley, California, sculptured by exfoliation. (Courtesy of the U. S. Reclamation Service)

posed to weathering agents, and the successive growths of roots, causing the soil to be made more open and accessible to weathering agents.

Burrowing animals, such as earthworms, ants, gophers, ground squirrels, and woodchucks, aid the action of weathering agents both by bringing fresher materials to the surface and by allowing more ready access of such agents to the surface materials. Earthworms perform a remarkable work of soil disintegration. They pass soil through their bodies in order to extract the vegetable matter from it, and in this way the bits of soil are ground up into still finer particles. It has been estimated that, in humid, temperate regions, the many thousands of earthworms per acre completely work over a soil layer from six inches to a foot thick once every half-century.

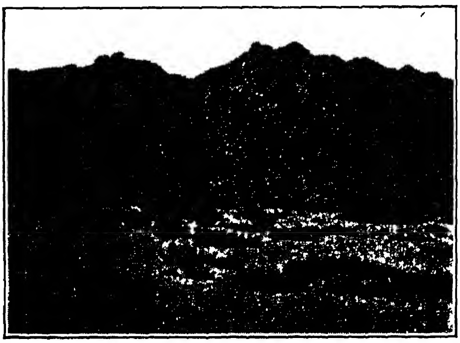

Fig 42

A ridge of granite crumbling under hot, arid-climate conditions West side of Coachella Valley, California (Photo by the author)

Action of Rain, Wind, and Lightning. — Mechanical weathering is accomplished in some measure on relatively loose rocks and soils by the impact of raindrops and by the force of the wind, whereby rock fragments are loosened from their positions. Lightning often shatters rocks in regions where electrical storms are frequent, but its total effect is relatively small.

Chemical Weathering

Solution. — Most rocks are only very slightly and slowly affected by the solvent action of perfectly pure water. Such water is, however, not found in nature because certain gases, particularly oxygen and carbonic acid gas, are always dissolved in it, causing the solvent power of the water to be notably increased. Pure limestone is slowly, but completely, soluble in such water, and the dissolved matter is carried away by streams. In an impure limestone, only the impurities tend to remain. When rocks, whose mineral grains are cemented, or held together, by

limy material, are subjected to the action of carbonated water, the limy material is dissolved and carried away, and the sand grains are left. Thus the rock crumbles Many waters have their solvent power increased by the presence of other acids obtained from decomposing organic matter, volcanic gases, etc. Natural waters thus charged with oxygen, carbonic acid gas, and other acids attack and dissolve minerals with greatly varying degrees of effectiveness. If even only one kind of mineral in a rock is but slightly dissolved, the adhesion of the mineral grains is lessened, and the rock tends to crumble. Some minerals are exceedingly resistant to solution Thus quartz is only slowly soluble even in hot, alkaline water. Such common minerals as gypsum and calcite are more or less readily soluble in hot, carbonated water. Salt is of course easily soluble in cold water.

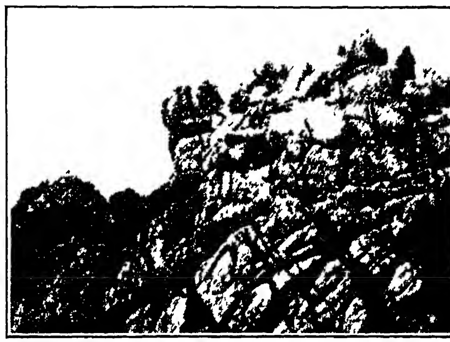

Fig. 43

A ledge of granite showing how joint cracks aid weathering Near Lone Pine, California. (Photo by the author.)

Carbonation, Oxidation, and Hydration. — Carbonic acid gas, which occurs in air, water, and soil, has the power of chemically uniting with, and altering the composition of, certain minerals of rocks. Thus many rocks contain the chemical elements calcium and iron with which carbonic acid gas may combine to form carbonates of calcium and iron. Such a process is called *carbonation*. The resulting carbonates are readily taken into solution and carried away by water, thus causing the rocks to crumble. A slow, but very important and widespread, process of this kind is the alteration of the very common mineral feldspar by carbonated water to kaolin (or clay), silica (or quartz), and a soluble carbonate. This action takes place during the decomposition of a hard, resistant igneous rock, like granite.

Oxygen occurs in air and soil, and dissolved in water. It is a very important chemical agent of decay of many rocks and

minerals. The process of *oxidation* consists in the chemical union of oxygen with any chemical element, as very often happens with the iron contained in such common minerals as pyrite, biotite-mica, hornblende (an amphibole), and augite (a pyroxene). The familiar rusting of iron involves oxidation, that is, a chemical union of the iron with oxygen of air or water.

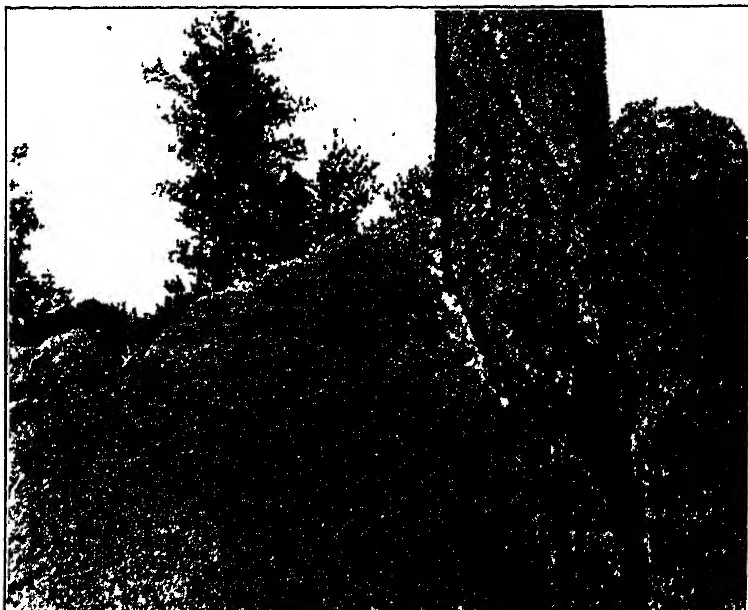

Fig 44

A growing tree splitting a boulder of granite. Custer County, South Dakota. (Courtesy of the U. S. Forest Service)

The process of *hydration* consists in the chemical union of water with certain compounds. The principle is well illustrated by the rusting of iron which, on exposure to air and moisture, first unites with oxygen to form iron-oxide, and then unites with water to become yellow or brown hydrated iron-oxide (the so-called "rust"). Many rocks contain iron not as such, but in chemical combination with other elements. When such iron-bearing minerals in rocks are subjected to the action of oxygen and water, the iron very commonly unites with both oxygen and water to form various

hydrated iron-oxides, ranging in color from yellow to reddish brown. Many of the striking colors of great rock formations of the earth have thus been produced. An excellent, large-scale example of gorgeous coloring so produced is the Grand Canyon of Yellowstone Park whose iron-rich lava rock has been highly decomposed.

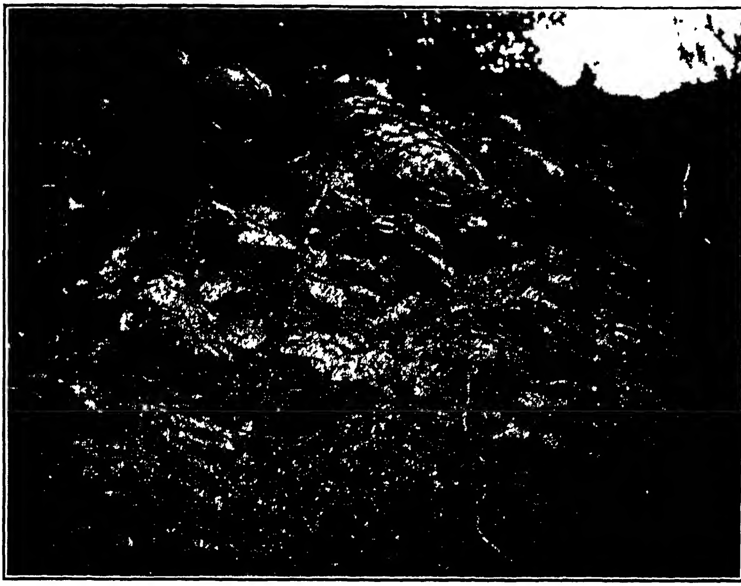

Fig 45
Spheroidal weathering in lava Griffith Park, Los Angeles. (Photo by the author)

Carbonation, oxidation, and hydration are all very important factors in the chemical weathering, or decomposition, of rocks. Increase in volume of the rocks affected is caused by all three processes, and the stresses and strains which develop as a result of volume increase tend to cause the rocks to crumble. In some cases the resulting materials, such as carbonates, are dissolved and carried away by water, thus increasing the porosity, and lessening the strength of the rocks affected.

Chemical Action of Organisms. — Bacteria are very abundant not only in soils, but also on bare rocks. One group has the

remarkable power of forming nitric acid from certain constituents (especially ammonia) of air, water, and soil, and this acid attacks and alters various minerals. Decaying plants, as well as roots of living plants, produce carbonic acid and other acids which alter the composition of various minerals in rocks.

Certain animals also bring about chemical weathering. Thus the soil particles which are worked over and carried by ants and earthworms are acted upon by organic chemical agents or acids secreted by these animals.

Spheroidal Weathering. — When water containing dissolved gases enters a rock mass (particularly one which is fine grained and homogeneous), which is divided into rectangular blocks by fissures, such as joint cracks (Fig. 96), the solutions work their way along the cracks and attack all surfaces of the rock with which they come into contact, and there cause decomposition which slowly eats into the blocks of solid rock. Not only do the edges, and still more so the corners, have greater surfaces exposed to the solutions, but also they are attacked from two or three directions at once with likelihood of being affected by the strongest solutions. The corners of the blocks of rock will, therefore, most rapidly be weathered, the edges next most rapidly, and the faces least. The new substances thus formed by oxidation, hydration, and carbonation are greater in volume than the unaltered material, and so "strains are set up which tend to separate the bulkier new material from the core of unaltered rock. . . . The squared block is by this process transformed into a spheroidal core of still unaltered rock wrapped in layers of decomposed material, like the outer wrappings of an onion" (Hobbs) They are usually embedded in thoroughly decomposed material. The process described is called *spheroidal* or *concentric weathering*, and the resulting boulders are called *boulders of decomposition* (Fig. 45). It is to be noted that they are produced mainly by chemical weathering, whereas boulders of exfoliation result from mechanical weathering.

Accumulations of Products of Weathering

Talus. — A mass of rock fragments of various sizes and shapes resulting from the weathering of a cliff or steep slope, and lying at the base of the cliff or slope is called *talus*. Temperature changes (exfoliation), and freezing and thawing of water in cracks, are the

principal weathering agents which produce talus material. As the fragments are loosened from the cliff or steep ledge they fall, slide, or roll down until the angle of slope is too low for them to continue. The angle of slope of a talus pile generally ranges from about 25° to 40°. The tendency is for the largest blocks of rock to accumulate toward the bottom of a talus slope because the momentum carries such masses farther. In mountainous regions of severe climate with great and rapid changes in temperature, the conditions are especially favorable for large accumulations of talus, such deposits attaining lengths and depths of hundreds, or even thousands, of feet (Figs 46, 47, and 48).

Fig 46

Lava cliff and talus slope near Northampton, Massachusetts (Photo by the author)

Boulder Fields Due to Weathering. — In many high mountains above the tree line, and in the Arctic regions, great, barren, flat, or only moderately sloping, rock surfaces are subjected to unusual rapidity of rock destruction mainly by frost action, that is alternate freezing and thawing of water in cracks proceeds with such rapidity that the surfaces are often almost or completely buried under masses of shattered and broken-up rock. Such rock fragments, which are generally angular in shape, may cover the bed rock from which they were derived to depths of 5 to 20 feet, or more. Boulder fields of such origin are wonderfully displayed at and near the tops of both Long's Peak and Pike's Peak in Colorado at altitudes of 12,000 to over 14,000 feet (Fig. 49).

In many boulder fields caused by weathering, the boulders are more or less rounded (Fig. 50). Fields of such boulders may result primarily from mechanical weathering Conditions are most favorable for their development in relatively dry and high regions not only because the process of exfoliation is there very effective in rounding off the original angular blocks of rock, but also because the winds tend to keep the finer products of weathering blown

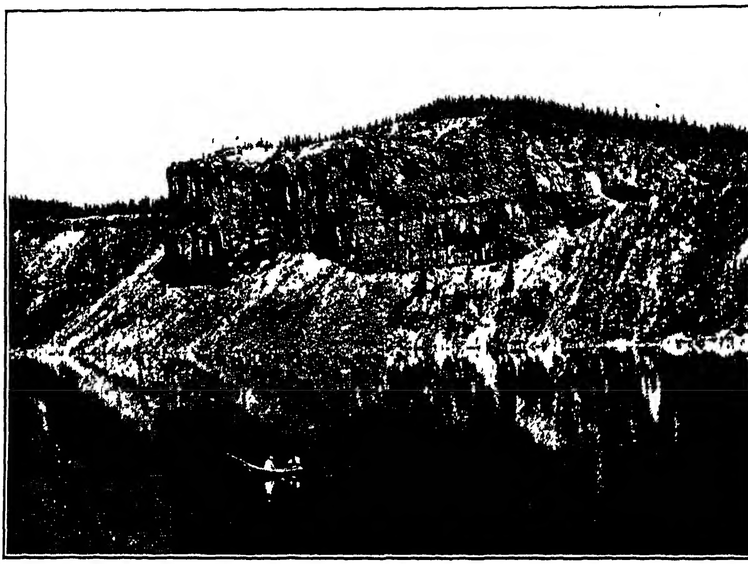

Fig. 47

A cliff of jointed lava and talus slope Crater Lake, Oregon. (Photo by J. S. Diller, U. S. Geological Survey)

away from between the boulders, thus keeping the bare surfaces of the latter constantly exposed to the weather

Fields of rounded boulders may also result primarily from chemical weathering Thus, the body of bed rock may be attacked much more vigorously by agents of decomposition along cracks, fissures, or more porous parts than it is in its more solid portions between the cracks or porous parts. There also may be local portions of the bed rock which are harder or more resistant to the weathering agents than the general body of the rock. In either

case, the tendency is for more or less rounded blocks of relatively fresh rock (Fig. 51) to accumulate in the midst of highly decomposed material. Removal of the decomposed material by rain, streams, or wind will tend to leave an accumulation of the boulders at the surface. Some of the boulders in this category are boulders of decomposition already described as resulting from spheroidal weathering.

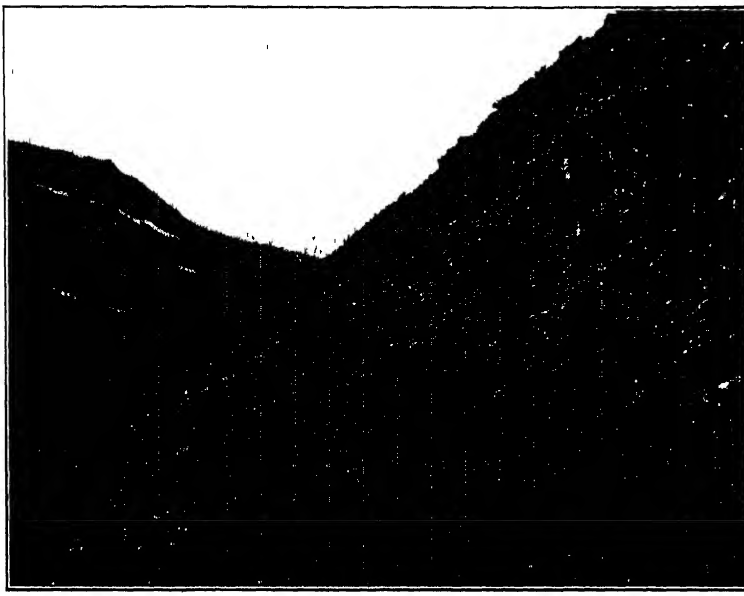

Fig. 48
Crumbling bed rock (upper right) and talus slope. Glacier Park, Montana. (Photo by the author.)

Mantle Rock. — Most of the lands of the earth are covered by a superficial layer of loose, earthy material called *mantle rock* which, wherever it occurs, rests upon the bed rock of the earth's crust. Where the bed rock is exposed at the earth's surface it is said to *outcrop*. There are two important kinds of mantle rock. One is the mantle rock which now rests upon the bed rock just where it was formed through the processes of weathering, that is, it is *residual mantle rock*, representing a direct accumulation of

weathered rock material. The other is mantle rock which has been carried to its present position upon the bed rock, mainly by water, wind, or glaciers, that is, it is *transported mantle rock*, representing an indirect accumulation of material mostly made up of products of weathering. Our present concern is chiefly with the residual rock mantle, while transported mantle rock is treated in several of the succeeding chapters The residual mantle does not rest by sharp contact upon the bed rock, but rather it grades

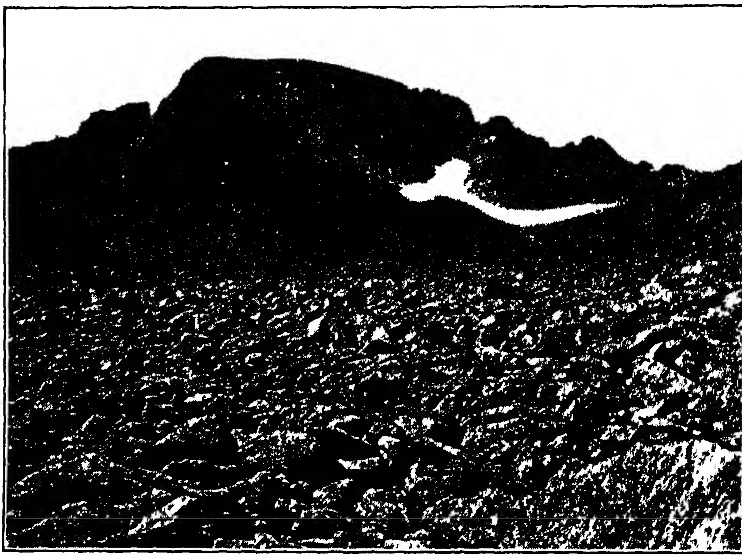

Fig. 49

A field of granite boulders resulting from frost action on north side of Long's Peak, Colorado (Photo by the author)

downward through partly weathered rock into unweathered rock. The transported mantle rock rests characteristically by sharp contact upon the bed rock from which latter it usually differs notably in composition. Although the processes of weathering are universal and unceasing in their action over all the lands, nevertheless there are many places where conditions favor removal of the products of weathering fully as fast as they are formed, and so bare rock surfaces are left exposed.

The very widespread mantle rock is of great geological im-

portance in several ways. Most of the vegetation of the land for countless ages has grown in its upper portion. It is the chief source of supply of the sediment carried by streams, and thus a great aid to erosion as we shall learn in a succeeding chapter. As an actual mantle it greatly retards the rapidity of weathering of the bed rock underneath it.

Soils. — The soils of the world are either directly or indirectly very largely the products of rock-weathering. To a very minor extent soils result from vegetation. In the strict sense of the word, *soil* is the relatively porous, fine grained, upper portion of the mantle rock containing an admixture of vegetable matter, and capable of supporting plant life. The term is, however, often used rather loosely. Just as we distinguish two general kinds of mantle rocks, so we must recognize two kinds of soils, namely, residual and transported. Residual soils here claim our chief attention because they are direct accumulations of products of weathering

Fig 50

Boulders of weathering Imperial Valley, California. (Photo by the author.)

Residual soil, with its admixture of decomposing vegetable matter causing it to have a more or less dark color, always grades downward into *subsoil* which usually contains fragments of partly decayed rock but little or no vegetable matter. The subsoil in turn passes by imperceptible change downward into partly decayed, so-called *rotten rock,* and this latter finally grades into the underlying, unaltered, so-called *fresh rock.* These various stages are well illustrated by Fig. 52.

Residual soils are very extensively developed in the southern states of the United States, and *transported soils,* left by the great glacier of the Ice Age, are very widespread over the northeastern states. True soils are usually not more than a few feet thick, but

soil plus subsoil and rotten rock may be scores, or exceptionally hundreds, of feet thick.

Considering the large number of different minerals and rocks which give rise to soils, and the varying conditions under which the materials are weathered, it is not surprising that there are many kinds of soils. In fact, probably no two soils from reasonably

Fig. 51
Rotten granite containing relatively fresh residual cores. Near Northampton, Mass. (Photo by the author.)

separate regions are just alike. Only a few of the more general soil types will be mentioned briefly. Thus, *clay* consists very largely of exceedingly finely divided kaolin. *Sand* is composed of sand grains, mostly quartz. *Loam* is a mixture of sand and clay. *Muck* is a very dark soil exceedingly rich in decayed vegetable matter. *Marl* is a soil rich in limy material, that is, in carbonate of lime. These very common kinds of soils show all sorts of gradations into each other.

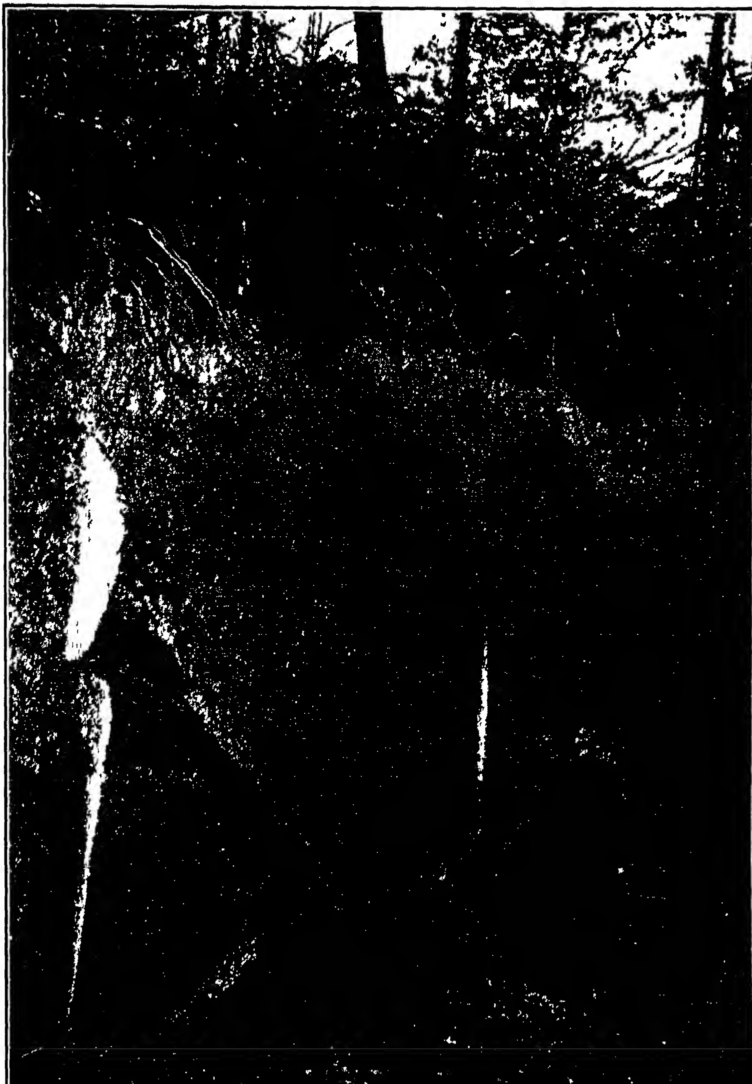

Fig 52

Fresh granite (at bottom) grading upward through rotten rock and subsoil into true soil. Washington, D.C. (After G. P. Merrill, U. S. National Museum.)

MOVEMENTS OF WEATHERED PRODUCTS

We shall now briefly consider some of the ways by which products of weathering are moved from their places of origin.

Attention has already been called to the accumulation of talus by the falling, rolling, and sliding of rock fragments which are loosened by weathering from cliffs and steep slopes. Closely

Fig 53
Differential weathering of hard sandstone (overhanging) and soft shale. Near Northampton, Massachusetts. (Photo by the author.)

related to this action is the movement of rock débris in so-called *rock glaciers* or "stone rivers" under certain conditions of cold climate. These are great masses of talus hundreds or even thousands of feet long, which slowly move down mountain sides or steep valleys, as in parts of Colorado. Externally they give somewhat of the appearance of a glacier. The motion results from gravity aided by alternate freezing and thawing of water which fills the spaces between the rock fragments.

Soil creep is a common process by which mantle rock and soil

move down slopes. When water-charged soil freezes, the rock fragments are lifted somewhat by the expansion at right angles to the slope or surface of the hill or mountain. On thawing, the rock fragments are pulled down vertically by gravity, and thus they move downhill a little. Repetition of this process causes the whole soil mantle to slowly move or " creep " down the slope.

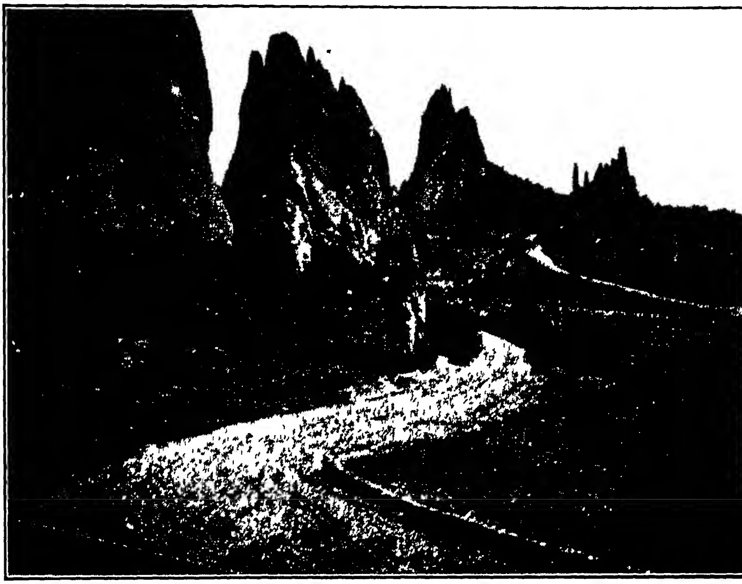

Fig 54

Effects of weathering and erosion of red sandstone. Garden of the Gods, Colorado. (Photo by the author.)

Sudden movements of masses of rock débris down mountainsides or hillsides are called *landslides*. Among various causes of such movements are earthquake shocks; undercutting of the masses of débris by streams, thus weakening the support toward the bottom; and saturation of the mass with water, thus increasing its weight and lessening the friction of the rock fragments. In many cases not only the soil or mantle rock, but also much bed rock of a mountainside, takes part in a landslide. This happened at Frank in Alberta, Canada, in 1903, when the whole face of a mountain several thousand feet high suddenly gave way, caus-

ing about 40,000,000 cubic yards of rock material to rush down into, and partly across, a valley (Fig. 133). Landslides are common, and many disastrous ones have occurred. Avalanches of snow also often carry much rock débris down with them.

Water, wind, and glaciers are by far the greatest agents of transportation of mantle rock, including soil. Water is most effective in humid regions; wind in arid regions; and glaciers in cold regions. All of these are very important geologically, and they are dealt with at some length in succeeding chapters. We shall here merely mention a few of the most important processes and effects involved.

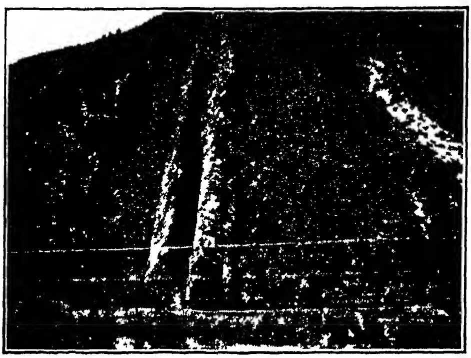

Fig 55

Differential weathering and erosion of vertical strata Devil's Slide, Weber Canyon, Utah (Photo by the author)

By the direct action of rain wash, loose materials not too thoroughly protected by vegetation are carried from higher to lower levels. Streams carry tremendous amounts of sediment from higher to lower levels, the general destination being the sea. Much of the sediment is washed directly out of the mantle rock, but a considerable quantity is developed through the erosive action of the streams themselves as explained beyond. Much sediment is deposited temporarily on valley floors and becomes *alluvium,* especially on flood plains during floods. Some stream-carried sediment is deposited in lakes, and much of it forms delta plains, and more widespread deposits, in the sea at or near the mouths of the streams.

Large quantities of dust, soil, and small rock fragments are carried by wind. Two important types of transported mantle rocks originating in this way are dune sand and loess (see pages 268 and 273).

Both valley glaciers and ice sheets (or continental glaciers) transport large quantities of rock débris. Thus, the vast glacier, which slowly moved over most of northern North America during

the Ice Age, carried along and deposited so much rock débris that it is now by far the most common mantle rock and soil over the central-northern and northeastern states of the United States.

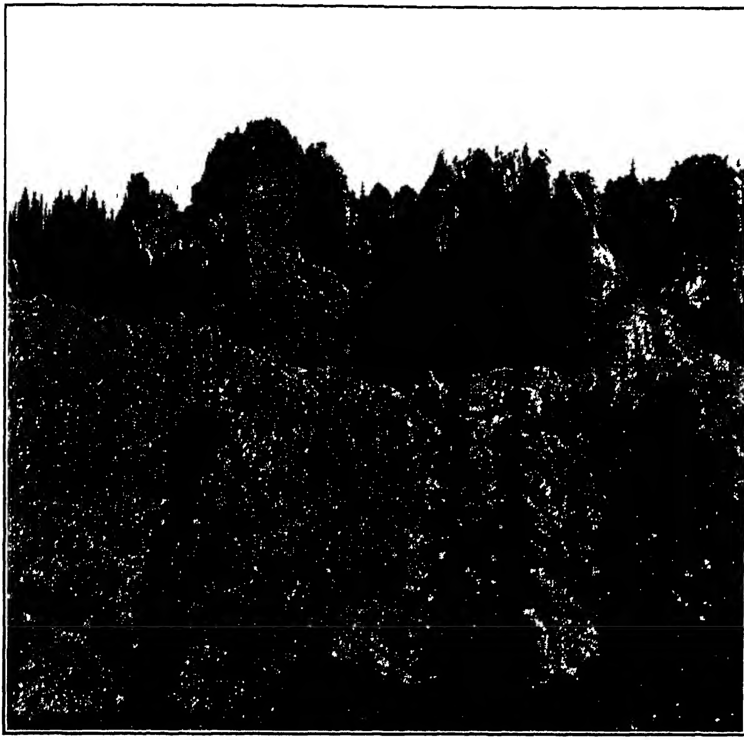

Fig. 56

Volcanic tuff intricately weathered and eroded Wheeler National Monument, Colorado. (Courtesy of the U. S. Forest Service.)

Sculpturing Effects of Weathering

Effects of Differential Weathering. — Most rock masses are not uniform in composition, texture, and structure. Some portions are, therefore, more readily attacked by agents of weathering than others, so that they are eaten into or etched out, while the more resistant parts are left to stand out in relief. All such cases of un-

equal weathering of rock masses are referred to as *differential weathering*. Such unequal weathering is a very common phenomenon to be observed in exposed bed rock almost anywhere. A few examples will suffice to make the principle clear.

Fig 57
A remarkably balanced rock resulting from unequal weathering Near La Veta, Colorado (Courtesy of the U S. Forest Service.)

Limestone or limy sandstone is particularly likely to become honeycombed, deeply pitted, or fluted where agents of weathering etch out the weaker and more soluble portions (Fig. 227).

Where a rock mass of any kind is transected by natural cracks called *joints* (see page 118), the tendency is for the cracks to become enlarged while the intervening masses of rock stand out more and more separately in relief. Where vertical joints cross-cut each other in closely spaced groups, leaving relatively large non-jointed blocks of rock between them, the tendency often is for the weather to remove the jointed material and leave the solid cores which themselves become less angular under the action of the weather. Among many excellent examples are the Cathedral Spires in the Garden of the Gods, Colorado (Fig. 54), and the many wonderful natural monuments near Douglas, Arizona (Figs. 58 and 59). Great joint blocks only partly etched out are wonderfully displayed in the walls of Zion Canyon, Utah (Fig. 97) A most remarkable maze of joint columns occurs in Bryce Canyon, Utah (Fig. 164).

Where veins (p. 22) or dikes (p. 140) of hard materials intersect ledges of weaker rocks, the vein or dike material often stands out in bold relief in the midst of the etched out general body of weaker rock (Fig. 122)

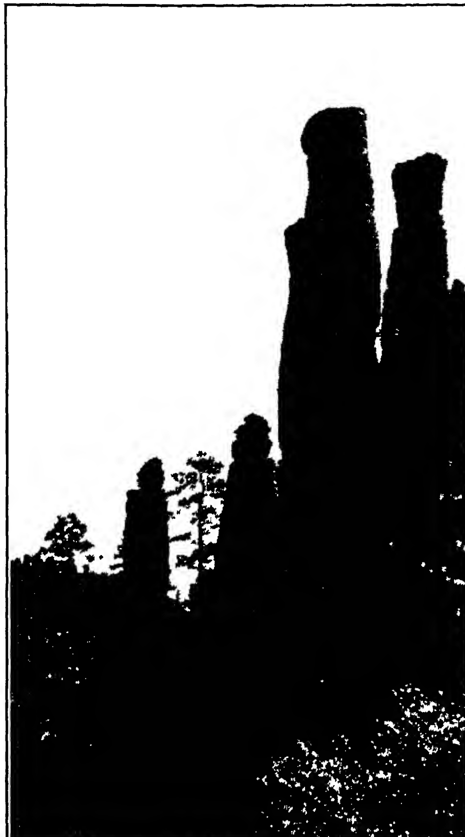

Fig 58
Joint columns resulting from weathering of rhyolite lava. Near Douglas, Arizona. (Photo by J J. Armstrong)

Rock formations which are arranged in layers (usually stratified) often possess variable degrees of resistance to the weather. Where such rocks are in horizontal position or gently inclined, the tendency is for the more resistant layers to form cliffs, or even overhanging ledges, while the weaker layers crumble down to talus slopes. Such differential weathering is grandly displayed in the Grand Canyon of Arizona (Fig. 163). If the rock layers are steeply inclined or vertical, the tendency is for the more resistant layers to stand out in relief as sharply defined ridges (Figs. 307 and 308).

It is evident, from what has been said, that differential weathering plays an important part in the detailed sculpturing of the land. Many of the more striking, minor features of landscapes, such as jagged peaks, pinnacles, ridges, and cliffs, have been so sculptured. Acting alone, however, differential weathering cannot proceed

very far because the weathered products must be removed (eroded) by some agent such as wind or running water in order that new surfaces of the rock may be exposed to the sculpturing processes.

Fig. 59
A pedestal rock resulting from weathering of rhyolite. Near Douglas, Arizona (Photo by J. J. Armstrong)

Sculpturing Effects of Exfoliation. — The modes of origin of boulders by the mechanical weathering process of exfoliation and the chemical process of spheroidal weathering, and also the manner of accumulation of such boulders into boulder fields have already been explained. There remains for brief consideration the more important topographic influence of exfoliation in the production of rounded or dome structures in rock ledges, hills, and even mountain peaks which may be called *exfoliation domes.* Hard, homogeneous rock masses, like granite with vertical joint cracks widely spaced, are, when exposed to rapid and great temperature range, exceptionally favorable for the development of large-scale exfoliation domes because the rock scales off in large slabs up to several feet thick, and scores or hundreds of feet wide and long. As the successive slabs peel off the rock masses gradually become more curved or concave, thus giving rise to curved surfaces and dome structures. Excellent examples are Stone

Mountain, Georgia (Fig. 40), and various mountains of Yosemite Park, California (Fig. 41). Where several sets of joints are closely spaced, and roughly at right angles to each other, the rock generally breaks up (under the weather) first into rectangular blocks resembling crude masonry (Fig. 96), and finally into a mass of boulders. Where only vertical joints are well developed, the rock tends to break up into jagged cliffs, ridges, and needle-like summits (Fig. 164).

Fig. 60

A remarkable pedestal rock resulting from weathering of rhyolite, and undergoing exfoliation. Near Douglas, Arizona. (Photo by J. J. Armstrong)

Valley Widening.—We shall learn in Chapter VII that most valleys owe their depth, and in part their width, to the erosive action of the streams which flow through them. In most cases, however, the width of their upper portions is due to weathering because, as a given stream cuts down and deepens its valley, the valley sides crumble under the action of the weather, and the resulting products move down the sides in the various ways already explained. The top and upper portions of valleys become wider and wider until finally

the slopes are so gentle that the weathered products move down them very slowly

Relation of Weathering to Erosion

The term *erosion* comprises all the processes whereby the lands are worn down. More specifically, it involves the breaking up, decay, and transportation of materials at and near the earth's surface by weathering and solution, and by the mechanical action of running water, waves, moving ice, or winds which use rock fragments as tools. The term "erosion" is one of the most important in the science of geology. It includes five processes as follows: weathering, corrasion, solution, pressure, and transportation. *Weathering*, as just explained at some length, causes much rock material to be broken up and decomposed. It is a very important process or factor of erosion. *Corrasion* consists in the rubbing or bumping of rock fragments of various sizes carried by water, wind, or ice not only against each other, but also against the general country rock, causing the latter to be worn away *Solution* is the simple process of dissolving rock material, mainly by water. *Pressure* exerted upon country rock by water, wind, or ice may cause relatively loose portions of the rock, such as loose soils and joint blocks, to be pushed away. By *transportation*, through the agency of water, wind, or ice, all rock materials loosened by the other four processes of erosion are carried along. Corrasion, solution, pressure, and transportation are discussed more fully in their respective relations to the work of streams, wind, glaciers, and the sea in Chapters VII, VIII, IX, and X.

CHAPTER V

INSTABILITY OF THE EARTH'S CRUST

Diastrophism

Meaning of Diastrophism. — The outer shell of the earth is unstable. Overwhelming evidence establishes the fact that it has been so for many millions of years. To the geologist the old notion of a *terra firma* is outworn. The inhabitants of an earthquake country could never have originated the idea of an unshakable, immovable earth. Earth-crust movements may vary from those which are so slow as to be imperceptible to those which are quick and violent. They may be upward, or downward, or sidewise. They may affect only small, local areas, or they may involve a large portion of either a continent or an ocean basin. The general term *diastrophism* covers all actual movements of the earth's crust of whatever kind or degree.

It is very important that the student should, early in his study of geology, be convinced of the fact that crustal disturbances (often profound ones) actually do take place, because this is one of the most fundamental tenets of the science. Sudden movements are, in the popular mind, more impressive and significant than the slow movements because they are more localized and evident, and frequently accompanied by destruction of life and property, as well as by obvious, though minor, changes in topography. Crustal movements which take place slowly and quietly are, however, often of much greater significance in bringing about profound physical geography changes, such as those which have affected the earth during its eons of recorded history.

There are, in a general way, two types of diastrophism. In one type, known as *epeirogenic movement*, there is either elevation or subsidence of a large or small portion of the earth's crust without notable compression or crumpling (folding) of the rocks, which latter may not have their former attitude changed, or they may become gently warped (upward or downward), or more or less tilted. Fracturing and dislocation (faulting) of the rock

masses often accompany such an epeirogenic movement which not uncommonly affects a considerable portion of a continent or sea floor. In the other type, known as *orogenic movement*, a relatively long, narrow belt or zone of the earth's crust is subjected to a force of compression, causing the rocks (usually strata) to be more or less crumpled (folded) and upraised into a mountain range. Our present purpose is merely to call attention to the general nature of epeirogenic and orogenic crustal disturbances, both of which are of great geological importance. Their significance will be better understood after a study of succeeding pages of this book, particularly the chapters on "Structure of the Earth's Crust" and "Origin and History of Mountains."

Various geological agencies, such as weathering, winds, streams, glaciers, and the sea, operate externally upon the earth, their general tendency being to cut down (erode) the lands and carry their waste into the sea. Such agencies would, if not interfered with, completely level the lands and destroy the continents in the course of time. Geological research has made it certain that such external agencies have operated upon the earth for countless ages, and yet the continents have by no means been destroyed. This is because the external agencies are now, and have been throughout recorded earth history, opposed by forces operating from within the earth, that is by diastrophic forces. Through diastrophism, elevation and recreation of lands have at least kept general pace with the external forces of destruction; ocean basins have sunk relative to continental areas, causing frequent withdrawals of sea water from areas temporarily submerged; and tremendous volumes of molten materials have been forced not only into the earth's crust, but also out upon its surface. Through lowering of land areas diastrophism has, in many cases, helped to destroy them as such, but on the average, diastrophic forces which upbuild lands (relative to sea level) have predominated over forces which have lowered them.

Datum Surface. — In land surveying the *datum* is the point, or horizontal line, or surface from which heights or altitudes of points or places are measured or reckoned. The geologist, for his study of the amount and rate of upward and downward movements of the earth's crust, must have some point, line, or surface as a datum. The sea surface is in general the most satisfactory

datum for it maintains an average tidal level (within narrow limits) throughout its vast extent. At the bottom of each topographic map published by the United States Geological Survey there is a statement that "datum is the mean sea level" which means that all elevations recorded on the map are reckoned from the average tidal level of the sea. It should not, however, be assumed that the sea level is, and always has been, fixed and constant. Not only is it a somewhat warped or irregular surface at any given time, but also it may rise or fall very appreciably. In other words, it is not a perfect datum, as will now be briefly pointed out.

It is well known that the earth is not a sphere, but rather a spheroid whose polar diameter is about 27 miles less than its equatorial diameter. Approaching the poles, sea level is, therefore, nearer and nearer the earth's center, and so varies with latitude. It is also a warped surface because near lands, especially where large, high mountain ranges lie close to shore, the surface of the sea is drawn upward and toward the lands by gravitational attraction, and so it is disturbed. In extreme cases such distortion is to be measured by a good many feet, but the amount is exceedingly small as compared to the size of the earth. Transportation of sediment into the sea causes rise of sea level by displacement of the water. Sinking of a portion of the sea bottom causes lowering of sea level. Accumulation of ice through snowfall to form great glaciers represents, in the main, water withdrawn from the sea, and hence a lowering of sea level, just as melting of such ice raises sea level.

None of the variations of sea level above mentioned ever amount to more than a few hundred feet. When it is realized that such variations are very small as compared to the vast expanses of sea and land; that they take place very gradually; and that changes of level between land and sea are generally much greater and more rapid, it is clear that sea level is, after all, a good datum. The records of earth history reveal the fact that many great and small changes of level between land and sea have taken place. Among the minor changes it is often impossible to tell whether it was sea level or land, or both at the same time, which rose or fell. In such cases, therefore, terms like uplift and subsidence, or elevation and depression, as applied to lands are commonly used by geologists in a relative sense only.

Evidences of Elevation of Land. — Only a very few of the thousands of definitely known cases of change of level between land and sea will here be briefly described. The examples are chosen to illustrate the more common principles involved. Some of these movements have taken place within the last few thousand years of clearly recorded human history, while others are much older, being records of the geological past.

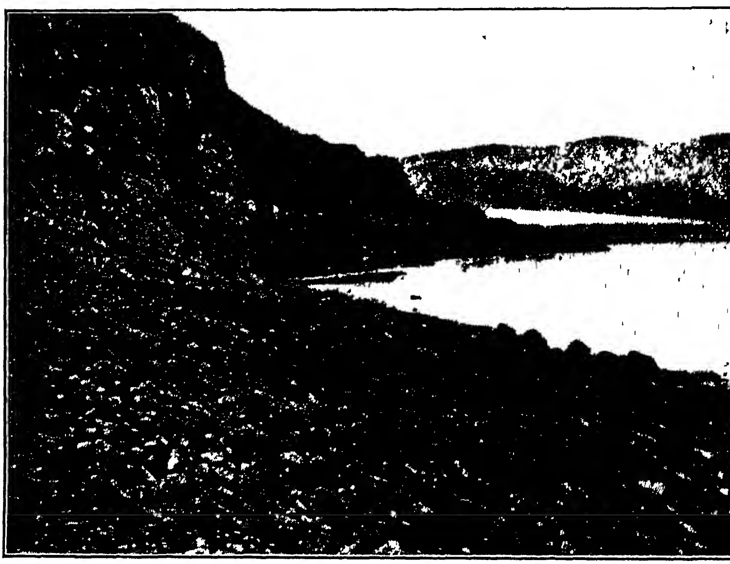

Fig. 61

Part of the shore of Disenchantment Bay, Alaska, which was suddenly uplifted 47 feet at the time of the great earthquake in 1899. (After Tarr and Martin, U S. Geological Survey.)

There are many authentic instances of moderate uplift of the land which have come under the observation of man A sudden diastrophic movement, resulting in a terrific earthquake, caused uplift of a part of the coast of Alaska near Yakutat Bay to a maximum of 47 feet in 1899 (Fig. 61).

Direct measurements by observing marks along the Baltic shore have proved that most of Sweden (excepting its southern portion) has risen to a maximum of seven feet during the last 175 years.

Old docks on the island of Crete in the Mediterranean Sea have risen as much as 27 feet within the last 2000 years.

Several rock ledges which were at, or a little below, sea level hundreds of years ago in the Baltic Sea are now distinct islands well above the sea surface.

About 100 years ago a portion of the coast of Chile rose abruptly several feet, causing a severe earthquake.

Evidence from old elevated shore features, including so-called "raised beaches," is very important. Thus, a succession of terraces cut by the waves of the Pacific Ocean are plainly preserved on the western face of the San Pedro Hills near Los Angeles, California. The highest and oldest of these terraces is over 1000 feet above the sea, while the lowest, containing many sea shells, is about 100 feet above tide. A somewhat similar succession of terraces occurs on San Clemente Island, about 50 to 60 miles off the southern California Coast (Fig. 62). Wave-cut terraces with remnants of rock not removed by the waves, occur well above sea level as illustrated by Figure 63. Sea caves formed by wave action are also above sea level in many places (Fig. 64). In Scotland such caves lie fully 100 feet above tide water. Raised beaches and shore forms in well-preserved condition up to hundreds of feet above sea level are common in many other parts of the world, as for example Scandinavia, Labrador, west coast of South America, and the West Indies. Many of these raised beaches are notably warped or tilted, thus proving that actual earth-crust movements have taken place, and not merely a lowering of sea level. A good illustration of this principle is found in the valley of Lake Champlain where the water deposits formed since the Ice Age now lie hundreds of feet above the present lake level, their

Fig 62

A succession of elevated marine terraces, on San Clemente Island, California. (After W. S. Smith, U S. Geological Survey.)

altitude increasing northward at the rate of more than two feet per mile.

Remains (fossils) of marine organisms at various altitudes up to many thousands of feet afford very strong evidence of uplift of land relative to sea level. There are almost countless numbers of examples. Thus, in the Rocky Mountains of the western United States and Canada sea shells occur in many places at altitudes of from one to over two miles (Fig. 2). The same is true

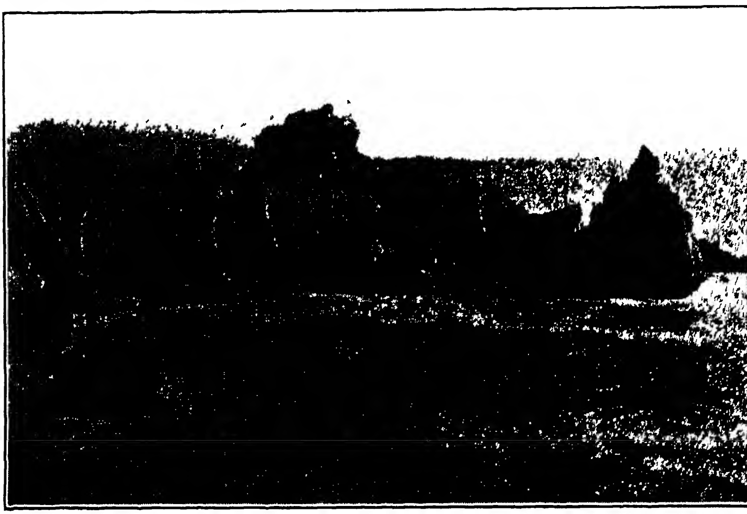

Fig. 63

Elevated marine terrace with remnants of rock which were not cut away by the ocean waves Near Port Harford, California. (After G. W. Stose, U S. Geological Survey)

in many other mountain ranges. In Tibet and northern India (Himalayas) fossil marine organisms have been found at altitudes of from three to four miles. In many of these cases the marine fossils are in highly disturbed (folded) strata of geologically recent age. Furthermore, strata of the same geological age lie at all sorts of altitudes in different parts of the world. For these reasons, and in the light of what we have already learned regarding the sea level as a datum, it is evident that such great, often differential, changes of level must be diastrophic rather than simply effects of lowering of the sea surface.

Well in the interior of continents, differential earth-crust movements are also known to have taken place. Thus high-level beaches of the vast ancestor of Great Salt Lake have been warped notably. Certain beach lines of ancestors of the Great Lakes have been tilted out of their original horizontal positions to the extent of hundreds of feet, since the Ice Age.

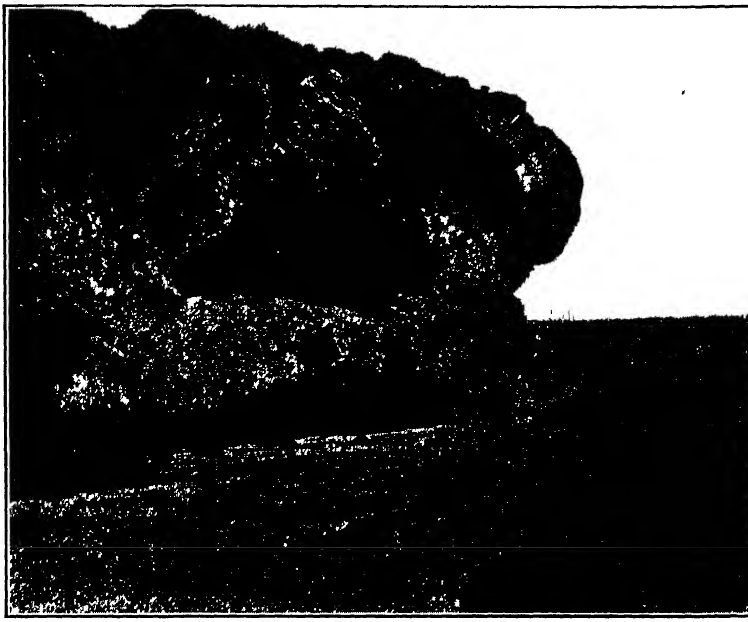

Fig 64

An elevated sea cave. Near Port Harford, California. (After G W. Stose, U. S Geological Survey)

Evidences of Subsidence. — Direct measurements have established the fact that the southern end of Sweden has sunk several feet during the last 175 years. This is of particular interest in view of the fact (as above stated) that the northern part of the same country has risen as much as seven feet during the same time, thus proving a case of differential diastrophic movement.

In certain parts of Crete old docks have (as already stated) been raised as much as 27 feet above water, while in other

portions of the same island remains of similar structures are below sea level, thus proving differential crustal movement.

Fig. 65
Two recently elevated marine terraces San Pedro Hills, California (Photo by the author.)

Portions of the coast of Greenland have sunk recently, as proved by the fact that certain human structures are there below tide water.

Submerged forests prove recent sinking of land in many parts of the world, excellent examples being around the coast of England, especially in Cheshire and Lancashire, and on the shores of the English and Bristol Channels, where numerous stumps of trees are well below tide-water level.

A good example of rapid movement of portions of a region in opposite directions at the same time is the Yakutat Bay region of Southern Alaska in 1899 where part of the coast suddenly rose as much as 47 feet, while another portion sank below tide level.

Fig. 66
The Champlain Sea stage of the Great Lakes history when the land stood hundreds of feet lower than to-day. (After Taylor and Leverett.)

Submerged valleys afford very strong evidence of subsidence, often to the extent of many hundreds of feet. Thus the valley of the Hudson River is very clearly traceable by soundings across the floor of the sea for 100 miles east of New York City (Fig. 67), proving that the earth's crust has there subsided fully 1000 feet since the valley was

carved out (eroded) by the river. Notable sinking of the land also has caused a flooding of the lower St. Lawrence Valley by tide water. San Francisco Bay was formed by geologically recent sinking of a portion of the Coast Range region, the Golden Gate marking the submerged channel of the combined Sacramento and San Joaquin Rivers.

In the study of examples of earth-crust movements, it should be clearly understood that a single district may show plain records of both depression and elevation. In such a case upward or downward movement may be succeeded by movement in the opposite direction. This principle is finely illustrated by the coast of Maine where the whole region sank hundreds of feet in recent geological time, allowing tide water to flood the mouths and lower valleys of all the rivers, thus giving rise to the deeply indented shore line. A partial reelevation (of 100 to nearly 200 feet) has taken place as proved by the clay deposits with marine shells along the coast, and for miles up the valleys.

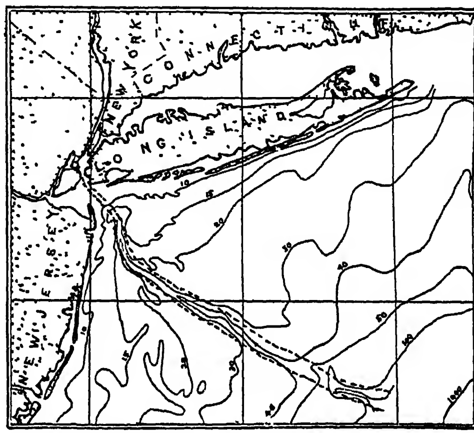

Fig. 67

Map showing the submerged channel of the Hudson River. Figures show depth of water in fathoms. (By the author, data from Coast and Geodetic Survey.)

Cause of Diastrophism. — The fact of diastrophism is thoroughly established. There is rather general agreement among geologists as to the proximate cause of diastrophism, but not in regard to the ultimate cause. The proximate cause appears to be unequal contraction, or shrinkage, of the earth. There is much evidence that the earth, or at least its outer (shell) portion, is heterogeneous, and that it has been shrinking for many millions of years. The fact that strata which, at various times and places, accumulated under water layer upon layer, in horizontal position,

to thicknesses of many thousands of feet, have been highly crumpled and folded into mountain ranges (see page 352) proves earth-crust shortening. In the development of a typical mountain range by this process, the crustal shortening is commonly 5 to 20 miles or more

Fig 68
The drowned Hudson River Valley at West Point, New York (After N Y. State Museum)

A general conception is that, as the earth shrinks, its outer shell or crustal portion is subjected to stresses and strains which are relieved occasionally by crumpling of zones of relatively weak rocks, usually strata. In other cases land areas may move upward or downward without crumpling, and with or without tilting. If the earth is a shrinking body, its whole surface must be undergoing a general downward movement toward the center. But, since the earth is a heterogeneous body, not all portions move downward at the same rate, and so the portions which move down less rapidly tend to stand out in relief, giving the appearance of uplift, although their actual movement is also downward.

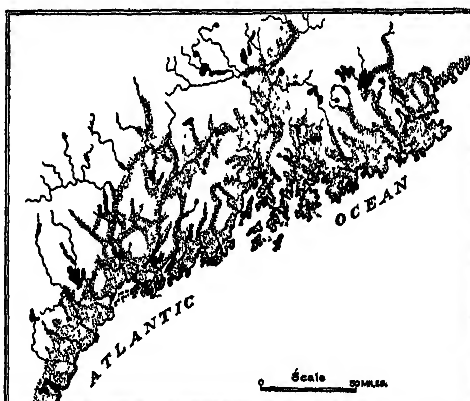

Fig 69
Sketch map showing the recently sunken and partly reelevated coast of Maine. (After Stone, U S. Geological Survey.)

Viewed very broadly, the earth may be divided into four segments — two oceanic (Atlantic and Pacific), and two conti-

nental (Eurasia-Africa and the Americas) It has been proved by actual test (gravity determination) that the materials of the oceanic segments are heavier than those of the continental segments. The oceanic segments are probably moving toward the earth's center faster than the continental segments. At the same time the great earth-segments are being more or less divided or broken up into smaller masses, some of which may be subjected to pressure in such manner as to cause localized actual uplifts, as in the folding and uplift of many mountain ranges.

It should be made clear, however, that the ultimate cause of diastrophism is, in our present state of knowledge, far from definitely known. That is, we do not surely know why the earth contracts, why it shrinks so unequally, or just how the shrinkage produces the various phenomena of diastrophism.

Earthquakes

Causes of Earthquakes. — Any sudden movement of a portion of the earth's crust, due to a natural cause, which produces a shaking or trembling of the ground is called an *earthquake.* The study of earthquakes is known as *seismology.* The impulse or shock which gives rise to the trembling originates at a greater or less depth below the earth's surface. Such shocks are known to originate in various ways.

Studies during the last fifty years have made it plain that the principal cause of earthquake shocks is the sudden slipping of portions of the earth's crust past each other along fractures, known as faults. The sudden shifting furnishes the impulse which sends out the vibrations or waves into the surrounding portions of the earth. The first great movement is usually followed for days, or even months, by a succession of after-shocks which generally decrease in number and intensity, though occasionally one or more of the earlier after-shocks may be very severe. Much evidence has been presented recently to support the view that the fracturing (faulting) of the rocks is the result of elastic strains which accumulate by slow shifting of neighboring portions of the earth's crust in opposite directions until the rocks can no longer withstand the strains, and that the only appreciable, sudden mass movement, at the time of the earthquake, takes place on one or both sides of the fracture, and within relatively few miles of it.

Such an earthquake may be regarded as simply a sudden manifestation of slower diastrophic movement. In an earthquake of the kind just explained, the main zone of shock, and, therefore, of destruction, is linear because the vibrations originate in the line of fracture. A very severe earthquake may be caused by a sudden slipping of ten to forty feet along a line of fracture fifty to several hundred miles long.

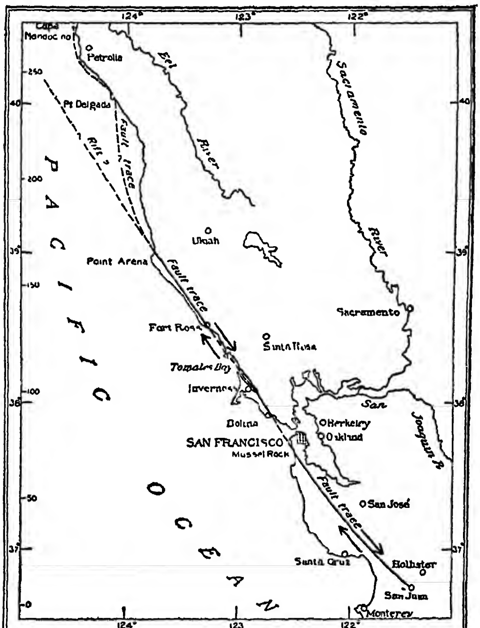

Fig 70

Map showing the trace of the great fault, sudden slipping along which caused the California earthquake of 1906 (After U. S Geological Survey.)

Another, though much less important, cause of earthquakes is volcanic activity. A violent or explosive eruption often causes the earth in its vicinity to quake. Earthquakes not uncommonly precede volcanic eruptions. In still other cases shocks often occur unaccompanied by eruptions in volcanic regions. It is generally believed that such earthquakes are caused by sudden, subterranean yielding of the earth's crust under the influence either of increasing pressure of volcanic gases or of shifting positions of molten rocks imprisoned within the earth and struggling to escape. Earthquakes of volcanic origin are, as a rule, much less severe and more limited in extent than those caused by fracturing of the earth's crust. In volcanic earthquakes the impulse or shock is centralized, rather than linear as in the fracture type of earthquake, and so the vibrations radiate from the center of disturbance into the surrounding region.

A minor cause of earthquakes is the force of impact of a great landslide or avalanche when it strikes relatively flat land at the base of a mountain Submarine slides also are believed to be a cause of earthquakes, as for example in some parts of the western coast of South America.

Another cause of small shocks is the sudden caving in or collapse of the roof of an underground opening (cavern).

The falling of a large block of rock from a cliff or the crest of a waterfall often gives rise to a slight shock. This has happened at Niagara Falls.

Frequency, Duration, and Extent of Shocks. — Earthquakes are exceedingly common. It is probably true that the surface of the earth is at no given time entirely free from earthquake vibrations. Earthquake recording stations in many parts of the world bear out this statement. Fully 30,000 earthquakes recognizable by the senses occur each year. A great many of these shocks are of course very slight. Only occasionally are the shocks very severe. Earthquakes which cause considerable loss of life and property occur, on the average, perhaps not more than once or twice a year. Earthquakes of varying degrees of intensity have been recorded in Japan at the rate of several per day, and in California at the rate of several per month, for many years, but most of them have been of very low intensity.

In New England, which is a region generally regarded as exempt from earthquakes, hundreds of shocks have been recorded within the last 300 years. Probably all but one (eastern New England, 1755) of these have been slight shocks which have caused little or no destruction.

The vibrations of earthquake shocks which are sensible to human beings last from a few seconds to several minutes In general, the greater the intensity of the shock, the longer it lasts. The average duration of shocks of considerable intensity is perhaps from one to two minutes.

Earthquake shocks of sufficient intensity to be noticed by man vary greatly in regard to the size of the region throughout which they may be felt. They may be felt over areas no larger than villages, or over considerable portions of continents The violent California earthquake of 1906 was felt over an area of several hundred thousand square miles. The Charleston, South Carolina, earthquake of 1886 was actually felt by people over an area of

2,000,000 square miles, and in states as far away as Wisconsin and those of southern New England (Fig 71). Severe earthquakes, like those just mentioned, actually shake the whole earth, though not enough to be generally recognizable by the senses, as proved by delicate recording instruments in many parts of the world.

Nature of Earthquake Waves and Vibrations. — In our consideration of earthquakes, the reader should clearly understand that the earth, instead of being an excessively rigid body, is, as a matter of fact, more or less elastic. A sudden impulse, therefore, sets a portion of the earth in vibratory (or earthquake) motion in somewhat the same manner that a large mass of jelly is set in vibration by a sharp tap on its containing vessel The vibrations or tremblings travel out in wavelike form into the earth in all directions from the source of the shock. Earthquake waves travel ordinarily at the rate of about two to three miles per second.

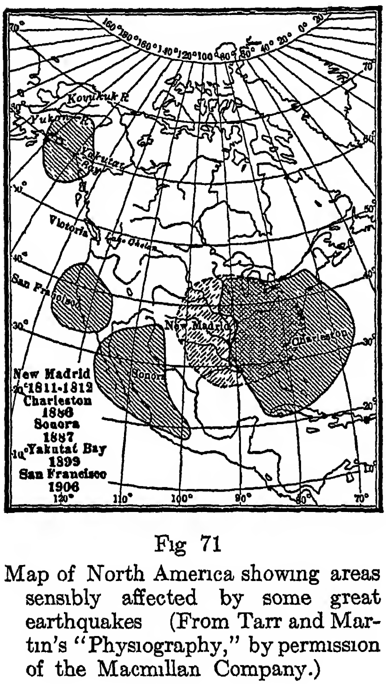

Fig 71

Map of North America showing areas sensibly affected by some great earthquakes (From Tarr and Martin's "Physiography," by permission of the Macmillan Company.)

When, as a result of a sudden shock, vibrations are set up in the earth, as in any solid, they take the form of waves within the earth which are of two important kinds, namely, *waves of compression* and *waves of distortion.* In the compressional (or longitudinal) waves, the particles move (vibrate) backward and forward in the direction along which they are transmitted. In the distortional (or transverse) waves, the particles move (vibrate) in a direction across the path of the wave transmission. On reaching the surface of the earth the transverse waves cause the rocking motion of the earthquake. Another kind of wave travels along the surface, and near surface, portion of the earth. The

exact nature of this wave is not known, but in a great earthquake it throws the ground into a series of actual undulations, somewhat like waves of water, which may be observed to rise in long, low, very swiftly moving waves, causing trees or tall structures to sway violently. The main shock is by some believed to be due to the joint action of transverse and surface waves. At distant points on the earth the kinds of earthquake waves are more or less separately recorded by a delicate instrument called a seismograph, as explained under the next heading. The actual amount of movement of a particle of earth during the passage of an earthquake wave, even the surface wave, generally is to be measured only by inches or fractions of an inch. The amount of bodily slipping or shifting of the earth's crust along and near the line of an earthquake fracture (or fault) commonly ranges up to 20 feet or more.

Seismographic Records. — Instruments of great precision and delicacy, called *seismographs*, have been constructed for the purpose of recording earthquake shocks. The fundamental principles involved are simple, but in actual construction a good seismograph is a complicated machine, a description of which will not here be attempted. In principle, a seismograph involves a heavy mass (say of metal) suspended like a pendulum. On the arrival of an earthquake shock the weight, due to its inertia, remains relatively still for some time, while the earth shakes under it. A marker, such as a pencil, which is attached to the suspended weight also tends to remain quiet during a shock. Now, if a recording plate or rotating cylinder is set in the earth immediately beneath, and in contact with, the marker, it is evident that the recording plate or cylinder will move with the earth during a shock, and thus be marked by the pencil point. Another weight suspended from a spiral spring keeps its position during up and down motions of the earth, and so affords a ready means of recording such motions. A seismographic record is called a *seismogram*. The best seismograms are recorded on rotating cylinders because on them the lines are not superimposed upon each other.

A good seismograph is practically automatic in its operation. Upon its several rotating cylinders, which are run by very precise clockwork, the north-south, east-west, and up and down components of motion; the exact time of beginning and ending (and

therefore duration) of the shock; and the intensity of the shock (usually magnified) are all recorded.

It has been deduced, from a study of seismographic records of distant earthquakes, that two sets of preliminary tremors immediately precede the main shock. The first preliminary tremors seem to be the longitudinal waves of compression, and the second preliminary tremors seem to be the transverse waves of distortion. Both of these pass through the earth from the place of origin of the shock to the seismographic station. The larger surface waves, which may be comb ned with transverse waves, pass around the earth in its surface portion in both directions from the seat of disturbance.

Earthquake Intensity. — In regard to their magnitude, two general classes of earthquakes may be suggested (1) those which disturb large sections of continents, and actually set the whole earth in slight vibration, and (2) those which affect only local areas with radii of not more than about 100 to 200 miles.

In regard to intensity of individual earthquakes, the so-called Rossi-Forel scale has been adopted quite generally. It is as follows:

I. *Microseismic shock:* recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.

II. *Extremely feeble shock:* recorded by several seismographs of different kinds; felt by a small number of persons at rest.

III. *Very feeble shock:* felt by several persons at rest; strong enough for the direction or duration to be appreciable.

IV. *Feeble shock:* felt by persons in motion; disturbances of movable objects, doors, windows; creaking of ceilings.

V. *Shock of moderate intensity:* felt generally by everyone; disturbance of furniture, beds, etc.; ringing of swinging bells.

VI. *Fairly strong shock:* general awakening of those asleep; general ringing of house bells; oscillation of chandeliers; stopping of pendulum clocks, visible agitation of trees and shrubs; some startled persons leave their dwellings.

VII. *Strong shock:* overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

VIII. *Very strong shock:* fall of chimneys; cracks in walls of buildings.

IX. *Extremely strong shock:* partial or total destruction of some buildings.

X. *Shock of extreme intensity:* great disaster; buildings ruined; disturbance of the strata, fissures in the ground; rock-falls from mountains.

Effects of Shocks. — Earthquakes are generally classed among the most terrifying of all natural phenomena because of the awful loss of life and property which sometimes results from them. Among the many very destructive earthquakes of modern times mention may be made of several as follows: Lisbon, Portugal, in 1755, when practically the whole city with its population of 60,000 was destroyed, Naples, Italy, in 1788, which cost 32,000 lives; Indus Valley, India, in 1819, which was very destructive of both life and property; Chile in both 1822 and 1835; Assam, India, in 1897, which killed many thousands of people and destroyed much property; California, in 1906, which directly and indirectly (through fire) destroyed much property, but not many lives; Messina, Sicily, in 1908, which destroyed much property and killed approximately 200,000 people; Tokyo, Japan, in 1923, which destroyed much of the city, and also Yokohama, with a loss of life of approximately 150,000.

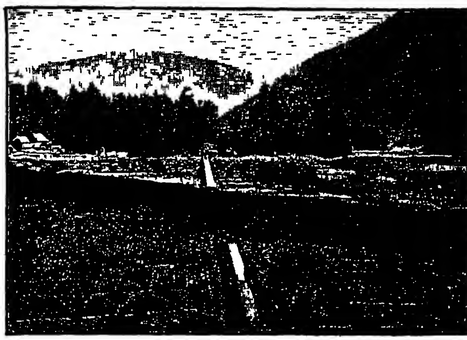

Fig 72

A fault scarp suddenly formed at the time of the Japanese earthquake of 1891. (After Kôtô.)

Earthquakes also cause certain changes in the earth's surface. In this connection it is important to keep in mind cause and effect of earthquakes. Thus the actual sudden shifting of portions of the earth's crust along either side of the line of fracture (fault), which is often accompanied either by the development of a fissure, or a steep declivity along the line of fracture (Fig. 72), is the

cause rather than an effect of an earthquake. Numerous changes are, however, direct effects of shocks, even at considerable distances from the seats of disturbance. Thus, the vibrations often cause landslides, especially in mountainous regions. Cracks and fissures, and local small elevations and depressions of the land, often occur, and they may affect surface drainage The disturbance of the earth's crust may cause old springs to stop flowing, or new springs to develop. An extraordinary subsidence occurred during the Indian earthquakes of 1819 when a tract of land covering some 2000 square miles near sea level actually sank a little below sea level. It very rarely happens, however, that even a great earthquake produces more than very minor topographic effects.

Fig 73

Map of the western hemisphere showing the principal earthquake regions (After M de Ballore)

Distribution of Earthquakes. — Although earthquakes are very widely distributed, so that no part of the earth seems to be immune from at least slight tremors, nevertheless most of them by far occur within two great rather crudely defined belts or zones, as shown by Figures 73 and 74. One of these belts almost encircles the great Pacific Ocean, and the other extends in a nearly east-west direction around the earth through southern Asia, the Mediterranean district, the Azores, the West Indies, Central America, the Hawaiian Islands, and the East Indies. In a study of 170,000 earthquakes, Montessus de Ballore found that nearly 95 per cent of them occurred within these two belts. It is an illuminating fact not only that the great majority of active and recently active volcanoes, but also that most of the youngest

mountains of the world are located within the two great earthquake belts. In fact it seems rather clear that both earthquakes and active volcanoes are only surface, or near-surface, manifestations of the great diastrophic forces which, at the present time, are operating chiefly within these two belts, but in the present state of our knowledge we cannot say why these great forces are there so active. A study of the ancient records of the earth (historical geology) shows that diastrophism has by no means always been especially vigorous within these two belts.

Fig. 74

Map of the eastern hemisphere showing the principal earthquake regions. (After M de Ballore)

Submarine Earthquakes and Tsunamis. — Many earthquakes are known to take place under the ocean, mostly within the belts just described, but obviously our knowledge concerning them is more meager than it is concerning earthquakes on land. Submarine disturbances are felt on shipboard, and ocean cables are sometimes broken by them. Among very recent, severe, submarine earthquakes, mention may be made of one which took place on the sea floor off the coast of Chile in the fall of 1922, sending a series of great sea waves upon the land. Another occurred somewhere under the south Pacific Ocean, sending water waves upon the shores of Hawaii. Such sea waves, known as *tsunamis,* are caused by the sudden movements of portions of the sea bottom. They are often miscalled "tidal waves."

Tsunamis may be from 100 to 200 miles from crest to crest, and 20 to 40 feet high, where they originate. They travel with a speed of hundreds of miles per hour, but in the open sea

they are scarcely noticeable because they are so broad and relatively low. Tidal gauge records show that certain tsunamis from Japan have crossed the Pacific Ocean, with height diminished to less than a foot, in about 12 hours. If a great tsunami starts reasonably near a coast it will pile up in passing into shallow water, and it may sweep upon the land in the form of a huge surge or breaker from 25 to 100 feet high. Such an earthquake sea-wave

Fig 75

Buildings wrecked by the Charleston, South Carolina, earthquake of 1886 (After Hillers, U S Geological Survey)

swept over part of the city of Lisbon, Portugal, in 1755 with destructive violence, and another in Chile (1868) carried a United States war vessel half a mile inland, and left it stranded.

Typical Examples of Great Earthquakes. — Our present purpose is to describe very briefly some selected examples of great modern earthquakes in order to better impress upon the reader many of the more important phenomena which they exhibit

New Madrid, Missouri, in 1811–1812. The many earthquakes which affected a large district around New Madrid, Missouri, in 1811–1812 were remarkable not only for their great severity, but also because they occurred well outside of the two major seismic belts of the world, and in a region far

from volcanoes or growing mountains. The first great shock came during the night of December 16, 1811. "Early in the morning another shock, preceded by a low rumbling and fully as severe as the first, was experienced. The ground rose and fell as earth waves, like the long, low swell of the sea, passed across its surface, tilting the trees until their branches interlocked, and opening the soil in deep cracks as the surface was bent. Landslides swept down the steeper bluffs and hillsides; considerable areas were uplifted; and still larger areas sank and became covered with water emerging from below through fissures or little 'craterlets,' or accumulating from the obstruction of the surface drainage. On the Mississippi, great waves were created which overwhelmed many boats and washed others high upon the shore, the return current breaking off thousands of trees and carrying them out into the river. High banks caved and were precipitated into the river, sand bars and points of islands gave way; and whole islands disappeared" (M. L. Fuller). Within a year after these first great shocks, hundreds of other shocks were felt, one on January 23, and several on February 7, 1812, having been very severe. Some of the shocks were felt on the Atlantic seaboard. It seems quite certain that these earthquakes were caused by slipping or readjustment of earth blocks along a general line or zone of fracture in the older rocks lying underneath the unconsolidated sediments of the Mississippi River flats.

Fig. 76

Ground torn up along the main fault at the time of the California earthquake of 1906. Near Point Reyes. (After G. K. Gilbert, U. S. Geological Survey.)

Indus Valley, India, in 1819. In the lower Indus Valley of India in 1819 a series of very severe and destructive earthquakes occurred during a period of several days. Within a few hours 2000 square miles of land sank a little below sea level, while a neighboring area of several hundred square miles rose as much as 10 feet.

Chilean earthquakes. Chile has been visited by a number of violent and destructive earthquakes during the last 200 years. Those of 1822 and 1835 both shook hundreds of thousands of square miles of the southern part of South America, and, just after each, long stretches of coastline were found to be elevated several feet. Those of 1868 and 1922 both caused great tsunamis to rush upon the land with destructive violence. In 1906 havoc was wrought in Valparaiso and vicinity, with after-shocks continuing for a long time.

Charleston, South Carolina, in 1886. A violent earthquake shook Charleston, South Carolina, and vicinity in 1886. "A slight tremor which rattled the windows was followed a few seconds later by a roar, as of subterranean

thunder, as the main shock passed beneath the city Houses swayed to and fro, and their heaving floors overturned furniture and threw persons off their feet as, dizzy and nauseated, they rushed to the doors for safety. In 60 seconds a number of houses were completely wrecked, 14,000 chimneys were toppled over, and in all the city scarcely a building was left without serious injury (Fig 75). In the vicinity of Charleston, railways were twisted and trains derailed Fissures opened in the loose superficial deposits, and in places spouted water mingled with sand" (W H Norton) It was felt by people in places as far away as eastern Iowa, Boston, Cuba, and the Bermudas It was caused by a rupture of the old rocks which underlie the loose Coastal Plain strata

Japan in 1891 The great Japanese earthquake of 1891 caused the destruction of 20,000 buildings and thousands of people within one minute. It perceptibly shook an area of over 240,000 square miles, but the principal destruction was confined to a thickly settled valley among the mountains in the central part of the island of Hondo It was caused by a sudden slipping of as much as 10 to 30 feet along a line of earth fracture for 40 miles (Fig. 72). The land on one side of the fracture dropped below that on the other side, leaving a terrace with a steep front as much as 20 feet high. An average of 500 aftershocks a month for five months succeeded the great earthquake.

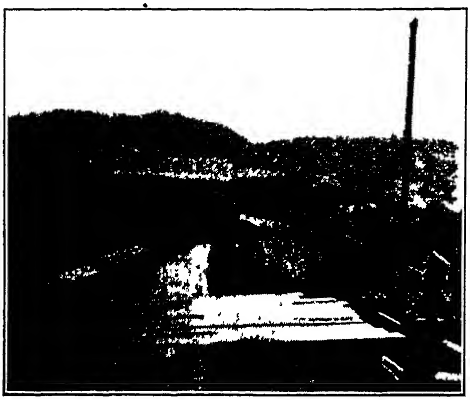

Fig 77
Road dislocated along the main fault at the time of the California earthquake of 1906 Near Point Reyes. (After G. K. Gilbert, U. S Geological Survey.)

Assam, India, in 1897. One of the greatest of all recorded earthquakes took place in the Assam region of northeastern India in 1897. Within two and one-half minutes an area nearly as large as California was laid in ruins, and notable changes in topography took place The ground was fissured in many places, and through numerous vents great quantities of water and sand issued. At one place a sharply defined terrace 35 feet high was developed. Movements of the earth's crust along one of the lines of fracture followed a winding stream, causing ponding of its water in some places, and waterfalls in others The land was thrown into waves, and it moved in a remarkable manner. Many landslides occurred

Southern Alaska in 1899 A series of very violent earthquakes shook the Yakutat Bay region of southern Alaska in 1899 when one part of the coast rose as much as 47 feet (Fig 61), while another part sank a little below sea level. "Vast quantities of snow and ice were avalanched from the mountains,

and, as a result of this abrupt accession of supply to the reservoirs of the glaciers, a wave of advance was started which, during the succeeding years, swept down the glaciers and caused notable change and advance in the glacier ends" (Tarr and Martin) A tsunami destroyed a forest along the coast

Fig 78

House on the main fault wrecked at the time of the California earthquake of 1906. (Photo by R L Humphrey, for U S Geological Survey.)

California in 1906 The California earthquake of 1906 ranks as the most violent shock recorded in the United States since the beginning of the twentieth century. The shock lasted about a minute. It caused a property damage, mainly in San Francisco, of several hundred million dollars, but fortunately the loss of life was not great It was caused by a sudden horizontal movement of one part of the Coast Range Mountains 2 to 22 feet past the other along a line of fracture (fault) for about 250 miles (Fig 70) Along the fracture, fences, water-pipes, and roads were notably dislocated (Fig. 77), and the ground was torn up (Fig 7). In San Francisco the greatest damage by far was accomplished by fire which started in various damaged buildings and quickly spread.

Fig 79

A view showing sharp contrast in resistance of buildings to earthquake action Santa Barbara, California, 1925 (Photo by the author)

Sicily in 1908. In regard to both violence and loss of life, the Messina, Sicily, earthquake of 1908 ranks as one of the greatest in the annals of human history. It has been estimated that between 150,000 and 200,000 people lost their lives in this frightful catastrophe which was caused by the sudden slipping of the earth's crust along a fault fracture

Japan in 1923. On September 1, 1923, radio messages startled the world with news of the frightful earthquake disaster which overtook the region including Tokio and Yoko-

hama in Japan Earthquake and fire destroyed a large section of the great city of Tokio, and Yokohama was almost completely ruined According to various reports, about 150,000 people were killed. The earthquake is said to have lasted for several minutes. It was caused by a sudden shifting of the earth's crust, amounting to hundreds of feet, along a fault fracture in the bottom of Sagami Bay

From the main island of Japan, which rises thousands of feet above sea level, there is a remarkably great and steep descent within a short distance to very deep ocean water (depth about 5 miles) This great, steep slope marks a portion of the earth's crust which is unusually lacking in equilibrium, and hence subject to rapid earth-crust movements.

CHAPTER VI

STRUCTURE OF THE EARTH'S CRUST

Structure Sections

It is usually an important part of the business of the geologist, in reporting on the geology of a region, not only to make a map depicting the surface distribution of the various rock formations,

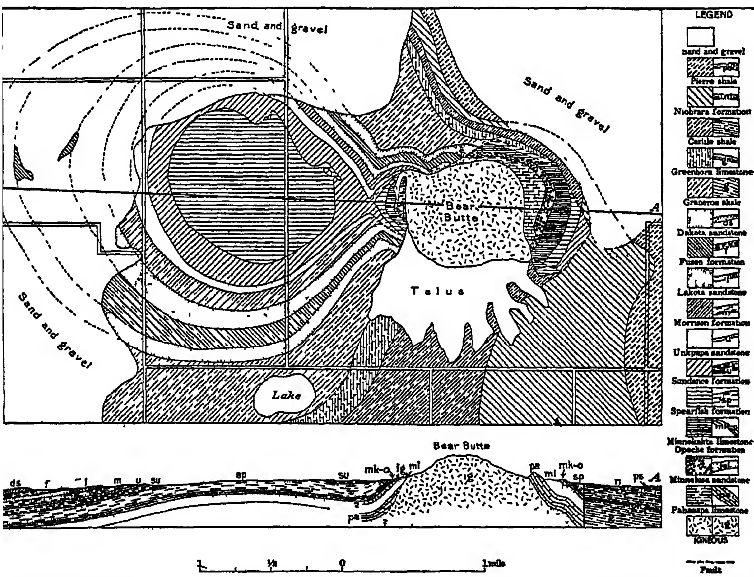

Fig 80

A geological map and structure section. Bear Butte, Montana. (By C. C. O'Harra, U. S. Geological Survey.)

but also to represent graphically the underground relations of the various formations by means of so-called "structure sections."

A *structure section* shows the relations of the rocks of a region as they would appear, from the surface downward, on the face of a

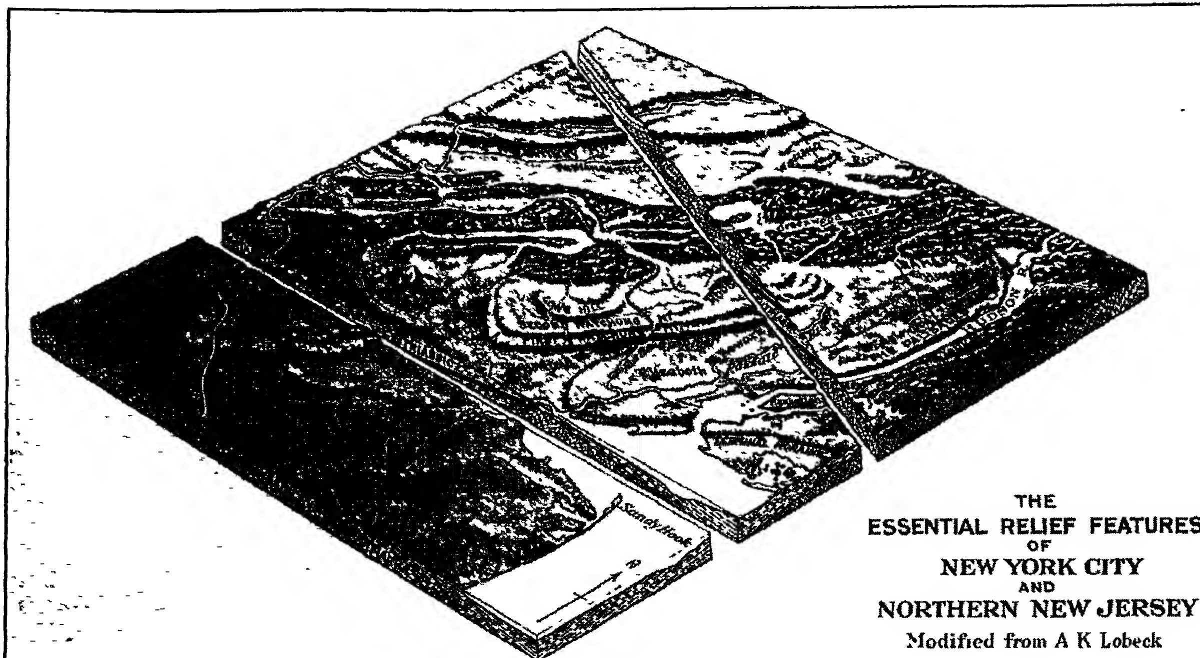

Fig 81

Relief map and structure sections of New York City and vicinity. (Modified by W. Belanske after A. K. Lobeck for the American Museum of Natural History)

vertical slice through a part of the earth's crust along a certain line. Thus, in Figure 80 the structure section shows the subsurface positions of the various formations along the line AA of the accompanying areal geologic map. In a block diagram (Fig. 81) it is feasible to combine with structure sections on two sides, either the surface distribution of formations, or the relief, or both. A careful study of the accompanying figures should serve to make clear the principle of the structure section.

Outcrop, Dip, and Strike

Outcrop. — Several terms are very commonly employed in dealing with the arrangement (*structure*) of the rocks of the earth's crust. One of these terms is *outcrop*, which means any surface exposure of the underlying bed rock. The term *rock exposure* is sometimes used as a synonym. It so happens that the bed rock formations are, in most regions, largely concealed under cover of soils, loose rock fragments, glacial deposits, vegetation, water, ice, or snow.

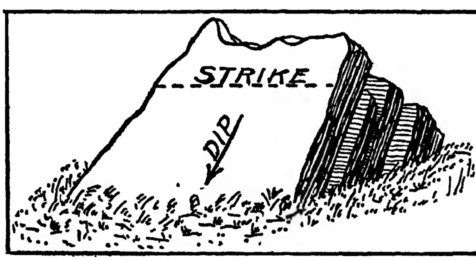

Fig 82
Sketch of an outcrop of strata illustrating dip and strike. (After J Geikie.)

In high mountains, or in other regions where erosion is proceeding rapidly, outcrops are generally much more numerous and extensive than in regions where sediments have recently been, or are being, deposited. It is very generally true that the surface distribution of rock formations, and the underground structures of a region, are worked out by a careful study of the outcrops. Where the geologic structure is simple, relatively few outcrops may suffice, but where it is very complex many outcrops must be found and carefully studied in order to determine the structure.

Dip and Strike. — In many regions, particularly in mountains like the Appalachians (including New England), the Rockies, and the Sierra Nevada, rock layers and formations are not only variously tilted or inclined, but also they show marked deviations

in trend across country. Two terms are used to designate such variations in tilt and trend — dip and strike. *Dip* is the inclination of a rock layer to a horizontal plane (or level surface). Two elements are involved, namely, *amount of dip* and *direction of dip*. By means of a compass provided with a small pendulum free to move over a graduated half-circle, amount and direction of dip are determined. Examples of note-book records would be dip 20°, S.40° W.; dip 65°, N.10° E., etc. *Strike* is the line of intersection of a dipping or tilted layer with a horizontal plane (or level surface). Or it may be defined as the direction (or trend) of a horizontal line on the surface of an outcropping rock layer. Strike is recorded thus: N.30° W., S 80° E., etc. When the direction of dip is recorded it is not necessary to give the strike because dip and strike are always at right angles, as clearly shown by Figure 82.

Folds

Zones of Flow and Fracture. — A *fold* is a bend in a rock layer, bed, or formation. Any rock mass, when subjected to sufficient pressure, or stress or strain, within the earth's crust, must either bend, flatten out, or fracture. Rock bends are folds, and fractures are joints, fissures, or faults. Bending and flattening are both comprised under the term *rock flowage*, which means a permanent change of form of a rock by pressure, but without notable fracture. Why do rocks sometimes bend, and at other times break? The earth has, for many millions of years, been a shrinking body. Many stresses, strains, and pressures have been set up in the crustal (outer) portion of the earth as it has been adjusting or accommodating itself to the contracting interior. Due to such forces, the rocks at and near the earth's surface have, in many places, been more or less profoundly fractured, and often subjected to sudden movements, while the rocks well within the crustal portion, that is usually from some thousands of feet to miles down, have, in many places, been folded, or even crumpled. For such reasons the surface and near-surface portions of the crust may be, in a general way, called the *zone of fracture*, while deeper portions may be called the *zone of flow*. Rocks (even the hardest) behave like plastic materials when subjected to great pressure well within the zone of flow, and, therefore, they bend or flatten out instead of break, because of the great weight of overlying material. This conclu-

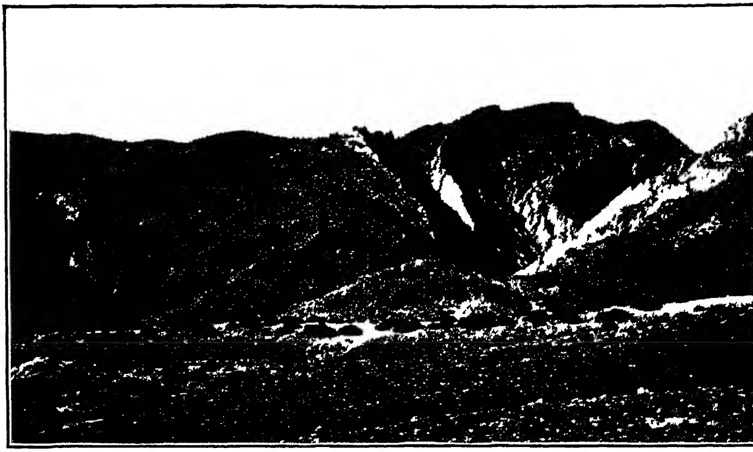

Fig. 83
An anticlinal fold with a strong downward plunge. Bighorn Mountains, Wyoming. (After Darton, U. S Geological Survey)

Fig. 84
An anticline in Paleozoic strata near Hancock, Maryland. (After Walcott, U. S. Geological Survey)

sion has been confirmed by laboratory experiments in which small masses of rocks have been subjected to slow, differential pressure equivalent to that which obtains miles within the earth. Such masses have been made to change shape notably without fracture.

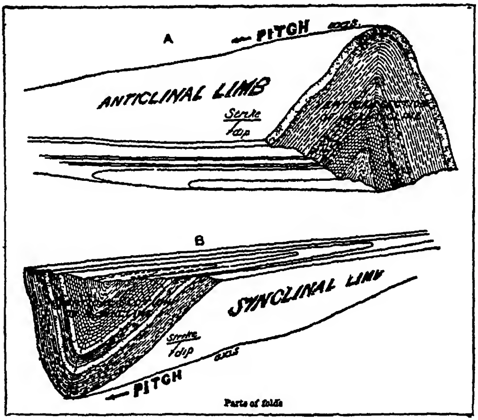

Fig 85

Diagrams illustrating parts of folds (After Willis, U S Geological Survey.)

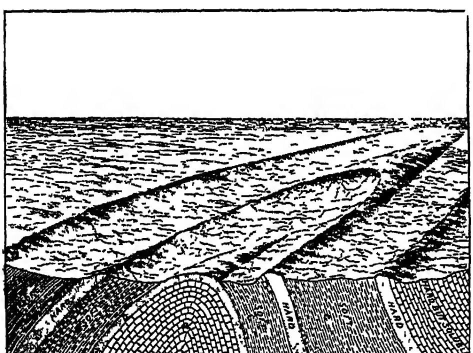

Fig 86

Perspective view and structure section illustrating a pitching anticline. (After Willis, U. S. Geological Survey)

The idea of depth should not, however, be too much emphasized in considering the zones of flow and fracture because there are other conditioning factors. Thus, very soft, plastic rock materials like wet clay at or near the surface will readily flow under pressure, while very hard, rigid rocks like granite will usually flow only when buried miles. Again, a very slowly applied pressure may cause a relatively hard rock to flow or bend much nearer the surface, while a quickly applied pressure may cause a relatively soft rock to fracture at a considerable depth.

Kinds of Folds. — As already stated, a rock bend is a *fold*. A simple arched-up fold is an *anticline* (Fig. 84). A *syncline* is an inverted anticline, or a troughlike

fold (Fig. 87) The flanks of the fold are its limbs, and the crest line (or the trough line) is its *axis*. The inclination of the axis to a horizontal plane is the *pitch* or *plunge*. These features, as well as dip and strike, are all clearly represented by the accompanying diagrams (Figs. 85 and 86).

Fig 87

A syncline near Hancock, Maryland. (After Walcott, U. S. Geological Survey)

When a fold has but one limb, that is when its layers incline in one direction only, it is called a *monocline*.

In an *isoclinal fold*, or a series of such folds, the limbs are parallel or nearly so. Such folds indicate great degrees of pressure (Fig. 88).

An *overturned fold* is one in which one limb is partly doubled under the other (Fig. 89), and a *recumbent fold* is an extreme case

of overturning in which the limbs lie in nearly or quite horizontal position.

The terms *anticlinorium* and *synclinorium* may be used to designate, respectively, great, complex, anticlinal and synclinal structures.

The term *dome* is sometimes applied to a special type of anticline in which the axis is nearly or quite reduced to zero, that is the limbs dip downward in all directions from the top of the fold. A synclinal *basin* is an inverted dome.

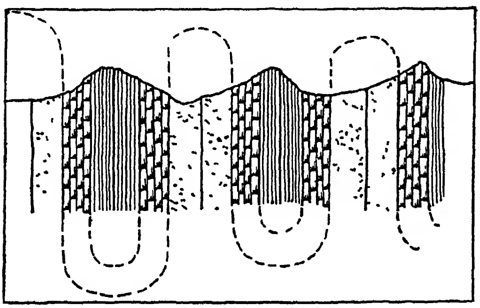

Fig. 88
Diagrammatic structure section showing isoclinal folds. (After Van Hise)

Such terms as *contortions, crenulations, crumplings, plications,* or *corrugations* are often applied to intense foldings of strata, especially on small scales (Fig 92).

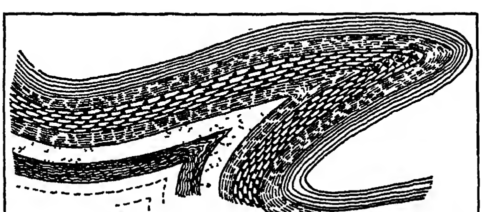

Fig 89
Diagrammatic section of an overturned fold. (After Van Hise.)

Under certain conditions, such as differential movement within a mass, local differences in rigidity of the rocks, etc., certain layers may become folded or contorted, while immediately adjacent layers are little or not affected (Fig 93).

Examples of Folds. — Folds range in both width and length from microscopic to many miles. Most folds, especially the large ones, develop very slowly, that is, the process may require thousands, or even hundreds of thousands, of years. Figures 90 and 92 illustrate small scale folds or contortions. The Uinta Range of northern Utah, many miles long and wide, is essentially a great, simple anticline whose limbs dip at very low angles. The Jura Mountains between Switzerland and France contain a

Fig 90
A small double fold. Monterey National Forest, California. (Courtesy of the U S Forest Service)

series of moderately folded, symmetrical, little eroded anticlines and synclines (Fig. 300). In parts of the northern Rockies of the United States, the anticlines and synclines are considerably squeezed together and rather deeply eroded. The Appalachian Mountains exhibit almost all known kinds of folds, and on almost all scales up to miles across. In Pennsylvania the rocks are less

severely folded than they are in the southern Appalachians (Fig. 302). The rocks of the Alps have been so severely folded as to give rise to an almost unbelievably complicated structure which is in part suggested by Figure 303.

Joints

Nature and Occurrence of Joints. — Almost all consolidated rock formations at and near the earth's surface are intersected by systems of fractures or cracks which divide the rocks into blocks of varying size, shape, and spacing When very little or no displacement of their adjacent walls has taken place, such cracks are called *joints.* In many places there are at least two sets of joints

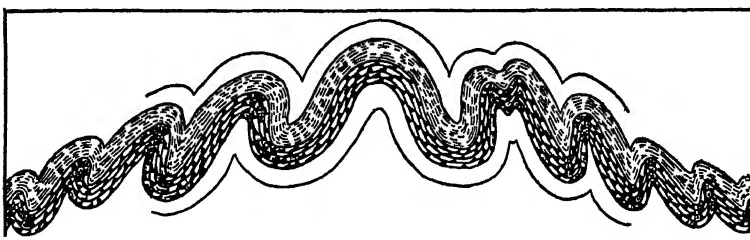

Fig. 91
Diagrammatic section of an anticlinorium. (After Van Hise)

crossing each other at high angles, and dividing the rock into prismatic blocks of roughly uniform shape and size (Figs. 96 and 97). In many other cases, however, numerous joints traverse rock formations very irregularly. The spacing of joints varies from a fraction of an inch to many yards. Single large joints are hundreds, and even thousands, of feet long and deep, as may often be seen in steep canyon walls and great cliffs. It seems quite certain that the whole zone of fracture of the earth is more or less jointed. Joints cannot exist below depths of approximately 12 miles because, as demonstrated by experiment, the tiniest cracks and crevices in even the hardest rocks cannot remain open under the conditions of tremendous pressure which obtain below such depths. Joints very often stand in approximately vertical positions, but they may lie in any position from vertical to even horizontal, especially when the rocks containing them have been

disturbed by folding or tilting. Joint faces often are remarkably smooth and straight for long distances, particularly in fine grained, hard rocks. Joint blocks are usually fitted together tightly, but sometimes there are very perceptible spaces between them, especially if the joints have been acted upon by the weather.

Fig 92

Contorted Tertiary strata Los Angeles, California. (Photo by the author.)

Causes of Joints. — Most joints in sedimentary, igneous, and metamorphic rocks are believed to have resulted from stresses and strains within the zone of fracture. Such joints may, on the basis of origin, be classified as *tension* and *compression joints*. When a portion of the zone of fracture is subjected to differential compression or torsional strain, owing to earth contraction, the rocks tend to fracture in two general sets of joints approximately at right angles to one another very much as can be shown by experiments with glass or ice. The crest portions of folds, where not too deeply buried, are often stretched to the breaking point, resulting in systems of joints. The sudden alternation of tension and compression in the zone of fracture during the swift passage of earthquake waves is quite likely a

Fig. 93

Contorted weak strata between non-folded hard rocks Near Russell, New York. (Photo by the author)

cause of many minor joints. It is evident that relatively slight stresses and strains may cause jointing because deep, well-developed joints are often found even in large areas of horizontal strata. Tension produced by contraction during the drying-out and consolidation of sediments when raised into land also is probably a minor cause of jointing In igneous rocks, systems of shrinkage

Fig. 94
Cleavage structure developed across bedding of sharply folded strata. Near Walland, Tennessee. (After Keith, U. S. Geological Survey.)

joints no doubt often develop when the masses of molten materials contract during the process of cooling and solidification within the earth's crust. Cracks thus formed are often filled with molten material forced up from greater depths to form what are called " dikes " (p. 140).

A kind of jointing of special interest is known as *columnar structure.* It often develops by cooling and contraction of either lava flows or masses of molten material which have been forced

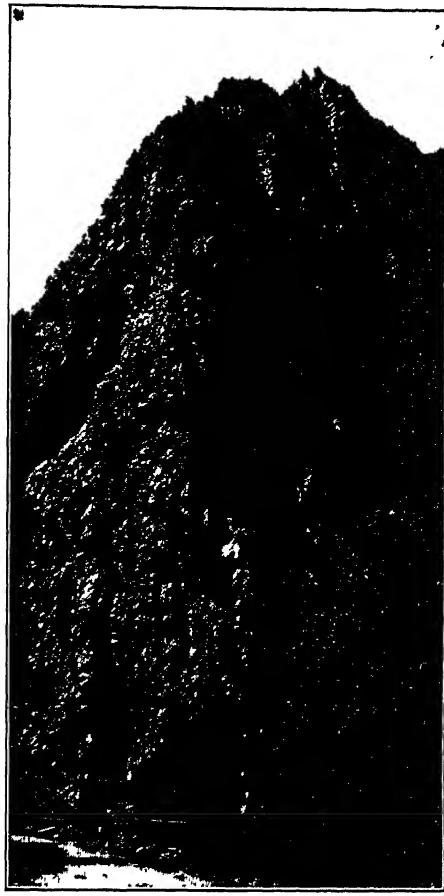

Fig 95

Steeply inclined and deeply eroded beds of quartzite many millions of years old in the much faulted and folded Wasatch Mountains near Ogden, Utah. (Courtesy of the Ogden Chamber of Commerce.)

into fissures near the earth's surface, during the process of solidification of the molten material. The effect is a splitting up of the body of rock into a system of close-fitting prisms of varying size and shape, but usually hexagonal. They are of all sizes up to several feet in diameter, and 200 or more feet in length. The columns always form at right angles to the cooling surface, so that in lava flows they are vertical, or nearly so, and in dikes they are usually approximately horizontal In some places this columnar structure is developed on large scales with a wonderful degree of regularity, as for example at the Devil's Postpile in California (Fig. 99); in the Columbia River Canyon; at Devil's Tower in Wyoming; and at the Giant's Causeway in Ireland. The Palisades of the Hudson near New York City are great, crudely developed, nearly vertical joint prisms 100 feet or more high.

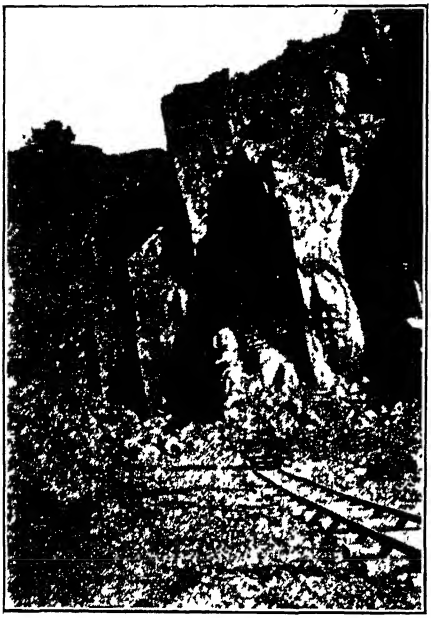

Fig. 96

Highly jointed plutonic rock (syenite). Near North River, New York. (Photo by the author)

Faults

Definition. — A *fault* is a fracture in the earth's crust along the face of which there has been slipping (or displacement) of the rocks (Fig. 101). The amount of such displacement varies from a fraction of an inch to many thousands of feet. Movement along a fault generally takes place suddenly, commonly involving distances up to 20 to 40 feet, or rarely even more. In great faults

the displacement represents the sum-total of many relativel minor, sudden movements.

Nomenclature of Faults. — Faulting is by no means always simple process, and, for a reasonable understanding of the struc tures involved, it is necessary to know the principal terms applie to faults, particularly to the amount and direction of movements. The accompanying diagrams should be carefully studied in connection with the definitions below given, and this should be supplemented with laboratory studies of models and maps, and also, if possible, with field observations. The components of faulting may be most readily comprehended by considering faulted strata made up of layers of various kinds, but of course the same general principles apply to faults in any kind of rock.

Fig 97

Great joint columns 1500 feet high in sandstone. Zion Canyon, Utah. (Photo by the author)

The *fault* Plane *surface* is the fracture along which the slipping or dislocation of the rocks occurs. It is better to call it a surface than a plane because it is seldom smooth and straight for any considerable distance.

Slickensides are the smoothed or scratched portions of a fault surface resulting from friction of movement of one earth-block past the other.

Fault breccia is the crushed, broken, and often recemented rock material commonly found along fault fractures, especially the larger ones, due to friction during movement. In many cases, however, faults are relatively clean, sharp breaks.

Fault trace or *rift* are terms applied to the trace of the fault on the earth's surface.

Drag is the term applied to the local bending of strata upward or downward adjacent to the fault surface according to direction of movement of the earth blocks. It is due to friction of the slipping mass along the fault. Drag is by no means always present.

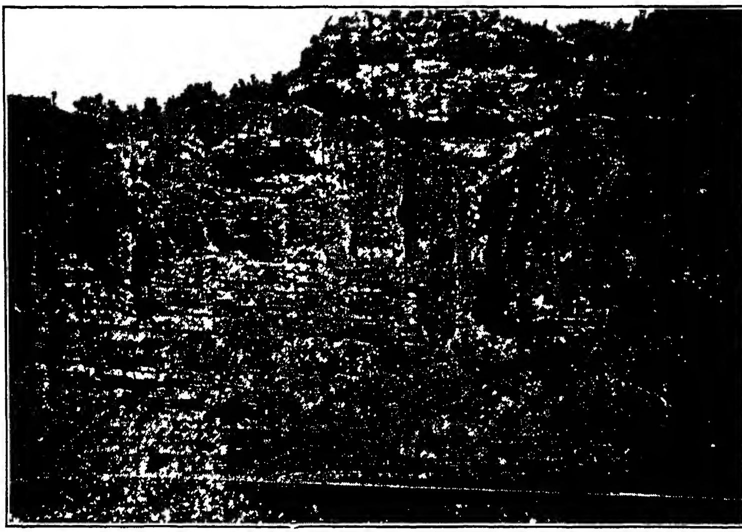

Fig 98

Vertical joints transecting horizontal sandstone strata. Canyon of the Colorado (Grand) River. Near Glenwood Springs, Colorado (Photo by the author)

Where one block of earth has moved down relative to the other along a fault, it is called the *downthrow side*, and the other is called the *upthrow side*

Where a cliff or steep slope forms on the upthrow side as a direct result of faulting it is called a *fault scarp* (Fig. 72). Fault scarps are almost always more or less eroded, sometimes to such an extent that no cliff, or steep slope, remains.

The rock immediately overlying a fault surface is called the *hanging wall*, and that immediately under it is called the *footwall*.

The *dip* of a fault, like that of a rock layer, is the inclination of its surface to a horizontal plane (or level surface).

The *strike* of a fault is its intersection with a horizontal plane.

The *hade* is the inclination of the fault surface to a vertical plane. It is always the complement of the dip.

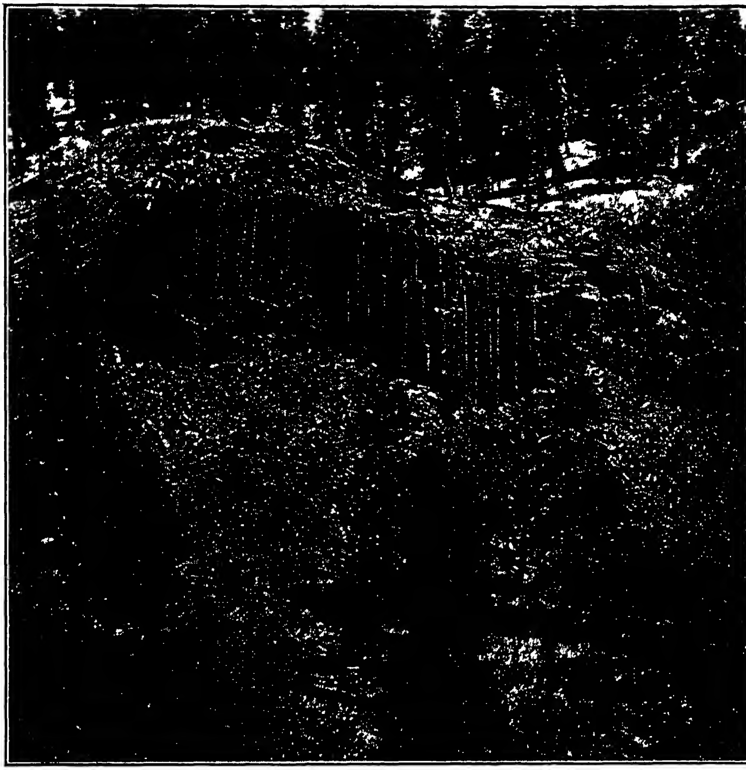

Fig 99

Remarkably developed columnar structure in lava Devil's Postpile National Monument, California. (Courtesy of the U. S. Forest Service.)

Slip is the distance a rock layer has moved on a fault surface. It represents the total displacement along the fault.

Throw is the vertical displacement of the fractured ends of a rock layer.

Heave is the horizontal displacement of the fractured ends of a rock layer as measured at right angles to the strike of the fault.

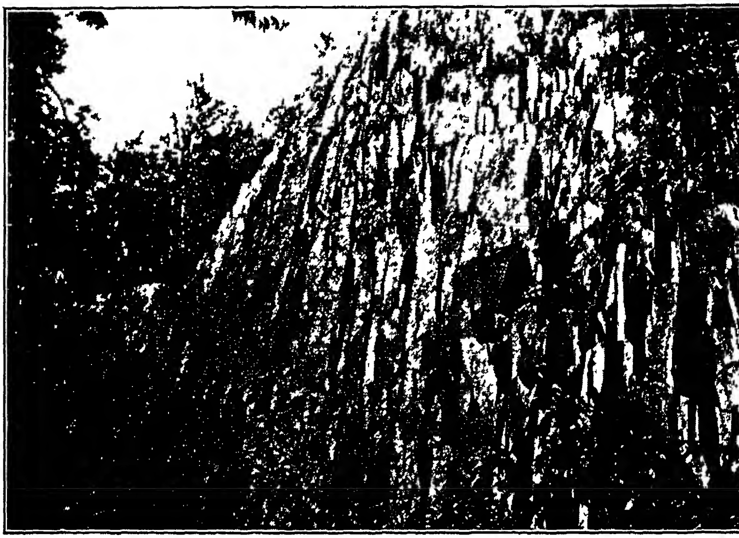

Fig 100
Crude columnar jointing in lava. Near Northampton, Mass (Photo by the author)

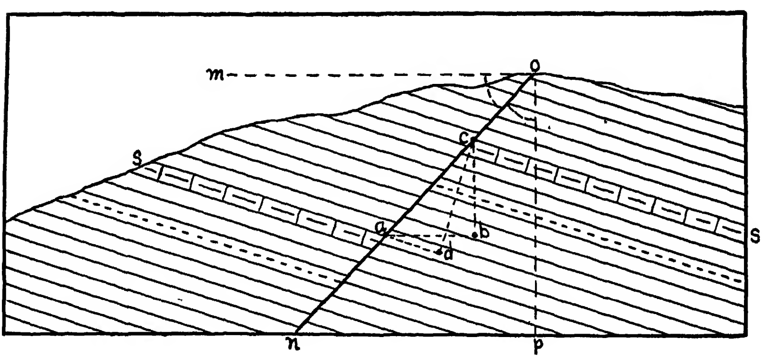

Fig 101
Structure section of an eroded normal fault *mon* = dip; *nop* = hade; *ac* = slip; *cb* = throw, *cd* = stratigraphic throw, *ab* = heave. (Drawn by the author.)

Stratigraphic throw is the thickness of the rock layers lying between the faulted ends of a given layer, as measured at right angles to the layers.

Offset or *strike slip* is the horizontal displacement of the fractured ends of a rock layer as measured along, or parallel to the strike of the fault.

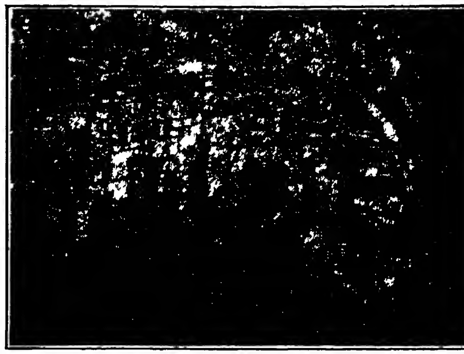

Fig 102

A zone of crushed rock (fault breccia) produced by faulting in hard, homogeneous, igneous rock. Keene Center, New York. (Photo by the author.)

A *dip fault* has its surface parallel to the direction of the dip of the rock layers involved, or nearly so.

A *strike fault* has its surface parallel to the strike of the rock layers involved, or nearly so.

An *oblique fault* is intermediate between the two last named.

A *compound* or *distributive fault* consists of two or more parallel (or approximately parallel) faults close together. In such a case the displacement has been distributed instead of being concentrated along a single fault-surface.

Step faults may be like those of a compound fault, but they are usually farther apart, and they must all dip in the same direction (Fig. 105).

A *graben* or *trough fault* is a block of earth, bounded by two or more faults, which has sunk relative to the surrounding mass of earth (Fig. 108).

A *horst* is a block of earth, bounded by two or more faults which has been elevated relative to the surrounding mass of earth

Kinds of Faults. — Five kinds of faults, based upon directions of movement along the fault surfaces, may be explained briefly as follows:

1. *Normal faults.* When the fault surface dips toward the downthrow side it is a *normal fault* (Fig. 103). In this case the hanging wall has slipped down an inclined fault surface relative

to the footwall. Figure 109 illustrates a very simple case of normal faulting in horizontal strata as it would appear unaffected by erosion Figure 101 represents an eroded normal fault in tilted strata. As shown by the figures, normal faulting involves a local extension of the earth's crust because the fractured ends of the rocks have been pulled apart horizontally by an amount measured by the heave. For this reason normal faults are some-

Fig 103

A small normal fault in sandstone and shale Near Northampton, Massachusetts. (Photo by the author)

times called *tension faults*. Normal faults usually dip at relatively high angles.

2. *Thrust faults.* When the fault surface dips toward the upthrow side it is a *thrust fault* (Fig. 112). In this case the hanging wall has been shoved, or thrust, up an inclined fault surface relative to the footwall. Figure 109 represents a simple case of thrust faulting in horizontal strata as it would appear unaffected by erosion. Figure 110 represents a more complex case where the thrust fault has been deeply eroded. As shown by the figures, the crust of the earth is relatively shortened by thrust faulting

because certain blocks of earth are partly shoved or thrust over others. For this reason thrust faults are sometimes called *compression faults* Thrust-fault surfaces are generally inclined (dip) at relatively low angles

Fig 104
Dikes of white granite in dark gray granite displaced by a normal fault. Near Pasadena, California (Photo by the author)

We may, in a general way, recognize three kinds of thrust faults, namely: (1) *Scission thrusts*, in which a fault surface develops independently of any older rock structure; (2) *fold thrusts*, which result from stretching of overturned and recumbent folds to the breaking point (Fig. 113); and (3) *erosion thrusts* in which extra-rigid, tilted formations, laid bare by erosion, are thrust over weaker underlying rocks.

Fig. 105
Step faults (normal) in a marl pit near Lomita, California. (Photo by the author.)

3. *Vertical faults.* When there has been upward or downward movement on either side of a vertical fault-surface, it is a *vertical fault*. The fault surface dips 90°, or nearly so, and there is neither hanging wall nor foot-wall.

4. *Horizontal faults.* When the movement has been wholly horizontal, or nearly so, on either side of a fault surface (either inclined or vertical), it is a *horizontal fault.* A sudden movement of this kind of 2 to 22 feet along a fault caused the

California earthquake of 1906, but fault movements of this kind are rare.

5. *Pivotal faults.* When one portion of an earth block moves upward, and another portion of the same block moves downward, on an axis at right angles to the fault, it is a *pivotal fault.* The block on one side of the fault works as though on a pivot with reference to that on the other side The effect is for the earth block

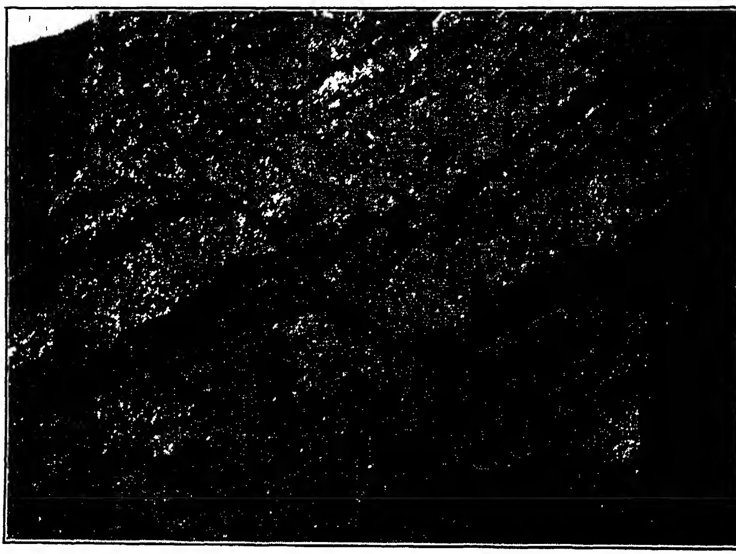

Fig 106

A small normal fault with secondary faults on each side Near Lomita, Los Angeles County, California. (Photo by the author)

on one side of the fault fracture to be in part upthrown, and in part downthrown.

Cause of Faulting. — The zones of flow and fracture in the earth's crust have already been described briefly in the discussion of the cause of folding. Rocks bend (or flow) when subjected to sufficient stress or strain in the zone of flow, while the same forces cause them to break in the zone of fracture. Every fault must, therefore, die out downward because the fracture grades into material which yields without breaking. The forces which cause

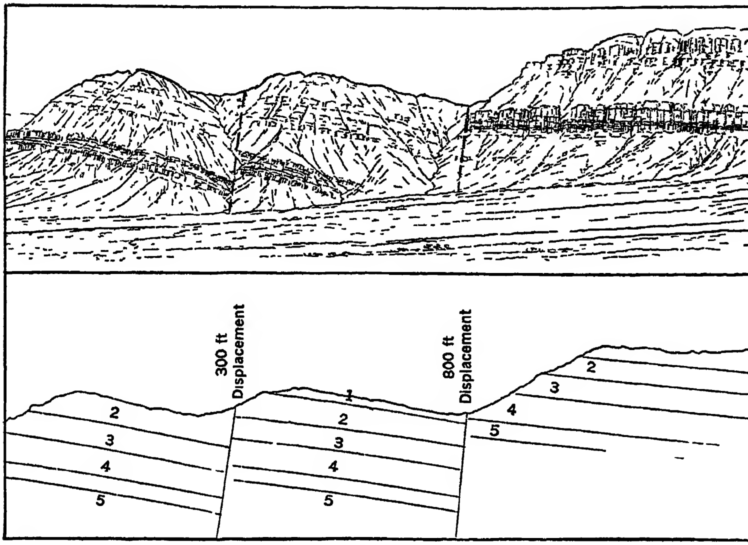

Fig 107
Eroded step faults (normal) and structure section Queantoweap Valley, Arizona (After U. S Geological Survey)

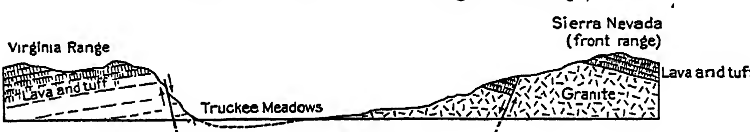

Fig 108
Structure section of a normal fault-block which has sunk about 3000 feet in western Nevada. (After U S. Geological Survey)

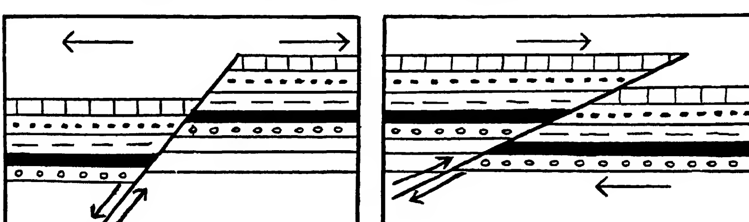

Fig. 109
Structure sections of a simple normal fault (*on left*) and of a simple thrust fault (*on right*). (By the author.)

faulting are compression, torsional strain, or tension (stretching) in the outer crustal portion of the earth Any such force may be exerted upon a rock mass until its breaking point is reached, when a fault results, usually accompanied by sudden movement. This movement relieves the force for a time, but the latter may increase slowly again to cause renewed movement along the old fracture, and so on repeatedly.

Great normal and vertical faults are generally associated with, and seem to result from, upward and downward movements of relatively large sections of the earth's crust, during the movements of which fault fractures develop. Great thrust faults are very often directly associated with compressive forces which cause zones of the earth's crust to crumple and become elevated into mountain ranges, the thrusts usually developing fairly well up in such masses.

The *ultimate cause* of faulting, as for that of folding, is a more difficult and uncertain matter, but by many geologists, including the author, it is believed to be intimately bound up with a shrinking earth, in the outer or crustal portion of which tremendous stresses and strains are, and for countless ages have been, set up.

Topographic Influence of Faulting. — Many relief features of the earth, both great and small, are direct or indirect results of faulting. If a considerable fault movement of any kind, except horizontal, should suddenly take place, a cliff or steep slope, called a *fault scarp,* would develop on one side of the fault (Fig. 72). Sudden movement of this kind is, as we have already learned, the most common cause of earthquakes. A single movement rarely produces a scarp more than ten or twenty feet high, but many repeated movements along the same fault may develop a scarp thousands of feet high, as along the eastern face of the southern Sierra Nevada (Fig 154). Even while such a scarp is developing through many thousands of years of time, the processes of weathering and erosion set to work to cut it down and diminish its steepness. Such eroded fault scarps are common in many parts of the world (Fig. 310).

In the course of time both sides of a fault, including the scarp, may be brought to the same level by erosion If, then, the rock on the upthrow side is weaker than that on the downthrow side, and the whole region should be elevated, erosion would be renewed and the weaker rock would be worn down faster, causing a

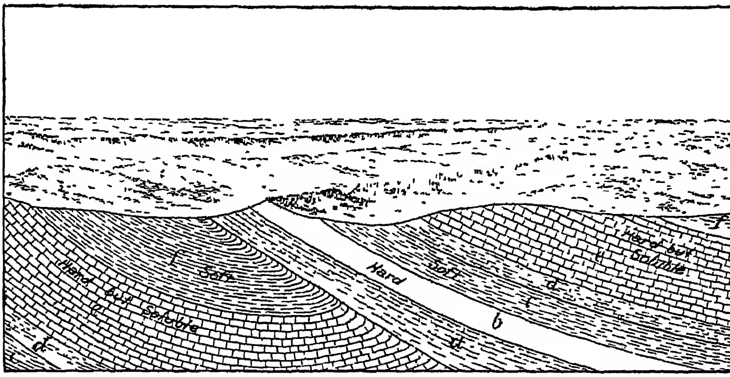

Fig 110
Structure section and perspective view of a thrust fault. (After Willis, U S Geological Survey)

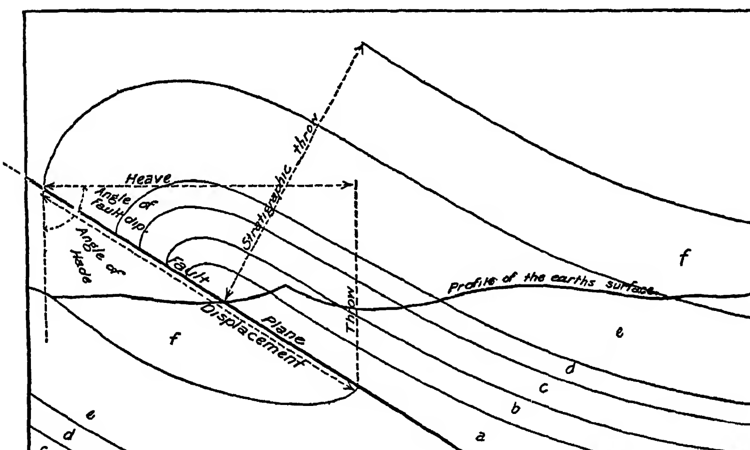

Fig 111
Diagrammatic section of the thrust fault shown in Fig. 110 (After Willis, U S. Geological Survey)

scarp to develop on the original downthrow side Or, if the weaker rock should lie on the downthrow side, the scarp would again develop on the upthrow side. Scarps thus formed by erosion

along faults are called *fault-line scarps* by Davis to distinguish them from true fault scarps. Fault-line scarps are common in the eastern Adirondack and Mohawk Valley regions of New York State.

Thrust faulting also often causes great and small changes in topography. Thus the whole eastern face of the Rocky Mountains in Glacier Park, Montana, is the front of a vast earth block several thousand feet high which has been shoved upon the Great Plains from the west. This fault scarp has been considerably cut into and indented by the action of rivers and glaciers (Fig. 114).

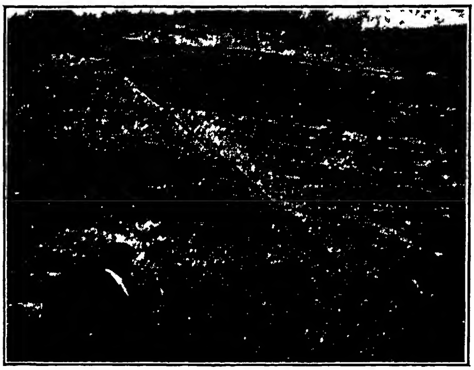

Fig. 112
A small thrust fault in Tertiary shale. Los Angeles, California (Photo by the author)

Thrust fault scarps, like normal fault scarps, may be, in the course of time, cut away and fault-line scarps developed instead.

In some regions, like parts of southeastern Oregon, Utah, and Arizona, steplike mountains and ridges, often in series, result from the tilting of fault blocks (Figs. 107 and 319).

A good many valleys of considerable size are the direct results of the sinking of earth blocks (*graben*) between faults. Examples are Death Valley, California; Truckee Meadows, California (Fig. 108); Jordan Valley, Palestine; and the Great Rift Valley of eastern Africa, hundreds of miles long, with its Lakes Albert and Tanganyika.

Many valleys, and systems of valleys, have been carved out by streams along faults because the work of erosion is, as a rule, more easily accomplished along fault lines of weakness in the rocks. A good example of such a drainage system is the southeastern Adirondack region of New York.

Some Examples of Large Faults. — We shall now very briefly describe some large faults and systems of faults, including a few of the greatest known.

The steep eastern face of the Sierra Nevada Range of California is bounded for hundreds of miles by a great, steeply inclined normal fault, the displacement along which has amounted to from one to three miles. In the Owens Valley region, the moderately eroded fault scarp rises very boldly to a height of over two miles (Fig. 154).

Displacement along the great normal fault, fully 200 miles long, at the western base of the Wasatch Mountains of Utah has amounted to many thousands of feet, with 3000 to 5000 feet of it still represented in the face of the steep, moderately eroded fault scarp (Fig. 310).

Most of the numerous nearly north-south mountain ranges of the great desert region between the Sierra Nevada and Wasatch Mountains are partly eroded, tilted, normal fault-blocks

In the eastern United States, the Adirondack Mountain and Mohawk Valley regions of New York state are cut to pieces by hundreds of vertical, or nearly vertical, normal faults, displacements along which are commonly from a few hundred to at least 2000 feet.

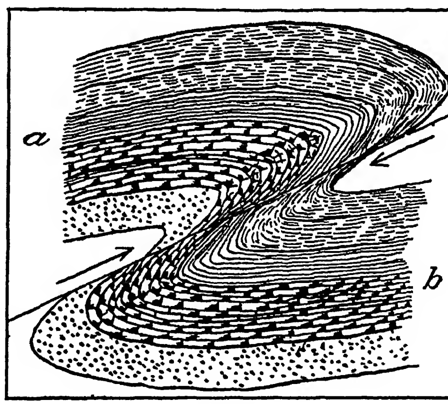

Fig 113
A sharp fold passing into a thrust fault. (After Van Hise, U. S Geological Survey)

Some of the great thrust faults are even more impressive. Thus, several thrusts in the eastern Appalachian region are each 100 miles or more long, with displacements on nearly horizontal, or undulating, fault surfaces of three to five miles or more.

The tremendous thrust fault, so clearly traceable for several hundred miles along the eastern base of the Rocky Mountains of the northern United States and Alberta, Canada, represents the bodily shifting of a large section of the mountain mass eastward over a low-angle fault surface for at least ten to fifteen miles (Fig. 114).

In Scotland, Scandinavia, and the Alps, there are also thrust faults of tremendous magnitude.

UNCONFORMITIES

When strata are deposited in uninterrupted succession, layer upon layer, they are said to be *conformable* Often, however, there is a break or interruption in the succession of strata which is

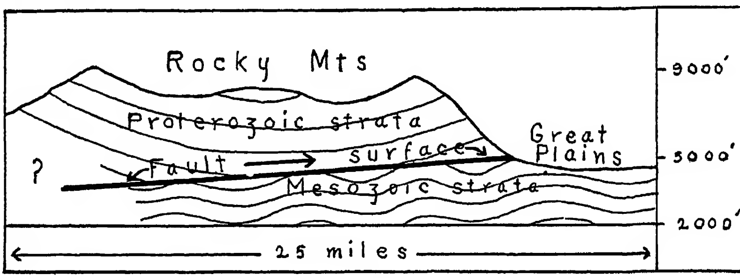

Fig 114

Diagrammatic structure section of the great thrust fault in Glacier National Park, Montana. (Drawn by the author.)

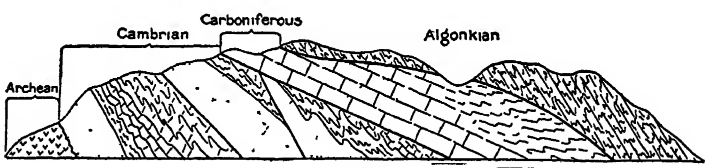

Fig. 115

Diagrammatic structure section of a system of thrust faults (heavy lines) in Ogden Canyon, Utah (After U. S. Geological Survey)

usually indicated by the fact that one set of strata rests upon the eroded surface of another set. In many cases strata rest upon the eroded surfaces of igneous or metamorphic rocks. The interruption may much more rarely be due simply to lack of deposition of sediments for a time, with no accompanying erosion. Sets of rocks whose regular succession is thus interrupted are said to be *unconformable*, and the structure is called an *unconformity*.

A mass of stratified sediments may be raised out of water and tilted, folded, or left practically horizontal, and then eroded.

Submergence would allow new sediments to deposit unconformably upon the eroded surface Renewed uplift and partial erosion may lay bare such an unconformity as illustrated by Figure 116 in which the underlying strata have been highly tilted and eroded, and by Figure 309 in which the underlying strata have been notably folded and eroded.

If the upper series of beds rests upon the eroded surface of tilted or folded strata, or of non-stratified rocks (igneous or

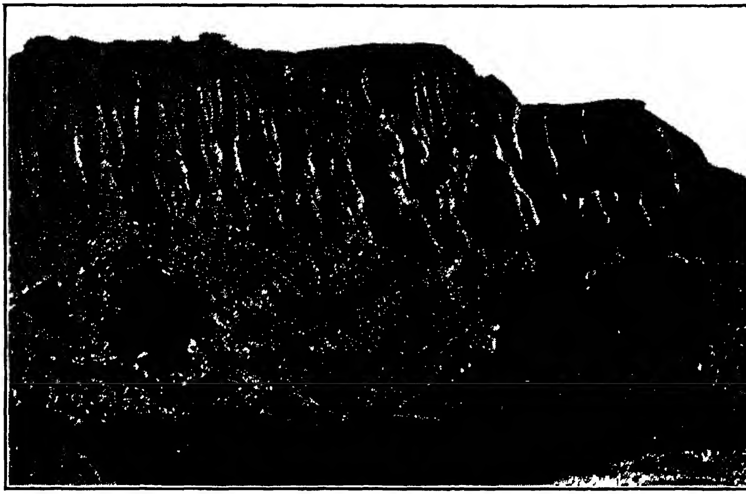

Fig 116

A conspicuous unconformity. Horizontal sands and gravels of Quaternary age resting upon tilted and eroded Tertiary shales. Near Port Harford, California. (After G W Stose, U. S Geological Survey.)

metamorphic), there is a very obvious unconformity called a *nonconformity*. If, however, two sets of beds separated by an erosion surface have their stratification surfaces practically parallel, there is a more or less deceptive unconformity called a *disconformity*.

A special phase of unconformity is known as *overlap* in which the younger (overlying) strata extend farther, that is they cover a wider area, than the older (underlying) strata, and so overlap the latter. Overlap will develop when strata accumulate upon a sloping area gradually subsiding under water.

Modes of Occurrence of Igneous Rocks

Plutonic and Volcanic Rocks. — In even an elementary discussion of the arrangement (structure) of the rocks of the earth's crust, the modes of occurrence of the igneous rocks must be considered. Igneous rocks represent either molten materials which

Fig 117

Horizontal beds of Ordovician limestone resting by unconformity upon Archeozoic gneiss. Montgomery, Canada. (After C D Walcott, U. S. Geological Survey.)

have been forced into the crust of the earth to cool and solidify below the surface, or molten materials, or fragments of once molten materials, which have been forced out upon the surface of the earth. The former are known as *plutonic* or *intrusive* rocks, and the latter as *volcanic* or *extrusive* rocks. Studies of igneous rocks in many parts of the world have shown that plutonic rocks are of far greater volume than volcanic rocks. Plutonic rocks

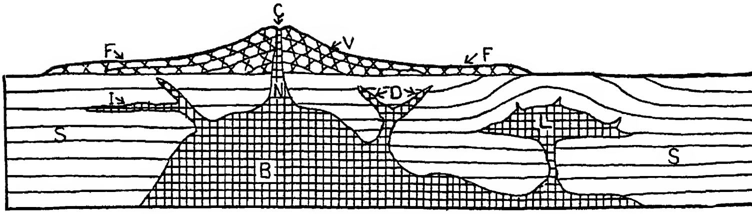

Fig 118

Diagrammatic structure section illustrating modes of occurrence of igneous rocks S = strata; B = batholith of plutonic rock; L = laccolith; D = dikes, I = intrusive sheet or sill, V = volcano, N = neck of volcano, F = lava flows, C = crater (Drawn by the author.)

Fig. 119

Basaltic dikes in granite Cape Ann, Massachusetts (After N. S. Shaler, U S. Geological Survey)

become exposed at the surface only as a result of erosion of the rocks which formerly covered them. Volcanic rocks are, no doubt, generally connected with deep-seated plutonic masses through intermediate rocks, reservoirs of molten masses of the latter

Fig 120

Small dikes of white granite in schist (After E. E Howe, U S. Geological Survey)

having always, or nearly always, been the sources of the volcanic materials.

Modes of Occurrence of Plutonic Rocks.—*Dikes.* A *dike* is a steeply inclined or vertical mass of igneous rock which was forced into a fissure when in molten condition. Dikes vary in width from less than an inch to several hundred feet, and in length commonly from a few feet to 10 or 20 miles. One in England is about 100 miles long Dikes are very abundant, a few among many regions being along the coast of Maine; Cape Ann in Massachusetts (Fig 119); and at Spanish Peaks in Colorado (Fig. 122). Dikes may be partially glassy, fine grained crystalline; or coarse grained crystalline, depending on the size, rate of cooling, etc., of the injected molten masses. They are sometimes arranged in roughly parallel groups, but often they form irregular, branching networks (Fig 120) cutting through rocks of any kind.

Fig 121

A sill (dark band) lying between beds of horizontal strata. Rio Grande River, Texas. (Photo by R. T. Hill.)

Sills. Where a mass of molten material (magma) has been forced as a sheet or layer between beds of strata in horizontal or gently inclined position it cools to form a *sill* or *intrusive sheet.* Sills vary in thickness from less than a foot to hundreds of feet

and they commonly extend laterally from a few acres to many square miles. An excellent example is the sill in the Hudson Valley near New York City, the outcrop of which is called the Palisades of the Hudson, in part forming a bold cliff several hundred feet high, facing the river for 30 miles.

Laccoliths. A *laccolith* is a dome-shaped mass of igneous rock which, in molten condition, has been forced between strata,

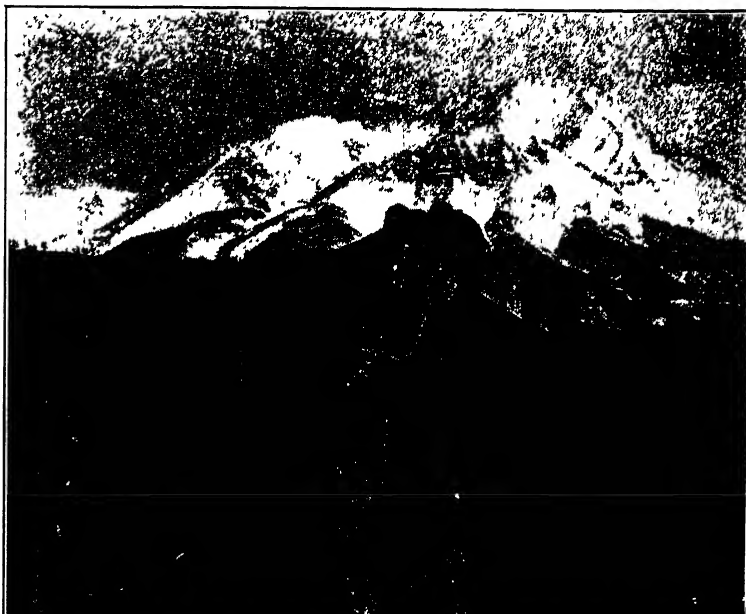

Fig. 122

Vertical dikes cutting strata and standing out in bold relief as a result of erosion W. Spanish Peak, Colorado. (After G W. Stose, U. S Geological Survey.)

causing the overlying rock layers to be domed or arched up. It has a more or less flat floor. The magma rising into the earth's crust through a relatively small opening becomes such a stiff fluid (or so viscous) that it can no longer penetrate the strata, so it spreads between them, and arches up the overlying beds (Fig. 118). Laccoliths commonly range in thickness from a few hundred feet to a mile in the middle, and in diameter from hundreds of

yards to several miles. The Henry Mountains of southern Utah consist of a series of laccoliths showing all stages of removal of the overlying, arched up strata. Various others occur in Utah, Colorado, Montana, and South Dakota. Bear Butte in South Dakota (Fig 123) is a very fine example of a large laccolith whose cap rock has been almost completely removed, leaving only the upturned edges of the strata as a ring around its base.

Volcanic necks. A *volcanic neck* is the hardened lava which fills the feeding channel (or conduit) of a volcano. It is roughly cylindrical in shape, and it commonly varies in diameter from a few hundred feet to a mile or more. Long continued erosion may finally cut away most of the relatively looser material of the volcano, leaving much of the core or neck of the mountain standing out in bold relief. There are excellent examples in New Mexico (Fig. 271) and Arizona, and in parts of Great Britain and France.

Fig. 123

A laccolith partly unroofed by erosion with upturned strata around it. Bear Butte, South Dakota. (After N. H. Darton, U S. Geological Survey.)

Stocks or bosses. The term *stock* (or *boss*) is applied to a fairly large body of plutonic rock, with crudely circular or oval groundplan, which, in molten condition, was forced into the earth's crust by cutting across the enclosing rock. Stocks usually increase in diameter downward. They vary in diameter from hundreds of feet to a number of miles. They are very common in New England and in the Piedmont Plateau of the eastern United States.

Batholiths. These are also called *bathyliths.* In all important respects, except size, they are like stocks. They extend over areas of hundreds, to many thousands of square miles, as for example in the southern Sierra Nevada Range; parts of the Rockies; eastern Canada; the Adirondack Mountains; New England; and the Piedmont Plateau. Stocks and batholiths,

being true plutonic rocks, are of course exposed at the surface only as a result of profound erosion of the overlying rocks. Granite, syenite, and gabbro are very commonly the rocks of stocks and batholiths.

Modes of Occurrence of Volcanic Rocks. — *Lavas.* Streams and sheets of molten materials (lavas) may pour out of volcanoes or fissures in the earth and cool to be successively covered by later flows. In such a manner a lava field may be built up to a thickness of hundreds, or even thousands of feet, and an extent of many square miles.

Fragmental materials. Through successive explosive eruptions of volcanoes, fragments of lava may be ejected in great quantities and scattered near and far. Thick and extensive beds of such materials, ranging in size from the finest dust to blocks weighing tons, may be built up. Both lavas and fragmental materials are more fully described in Chapter XI.

CHAPTER VII

THE WORK OF STREAMS

Introduction

Erosive Importance of Streams. — All things considered, running water is the most important of the three great agents of erosion — water, wind, and ice About 30,000 cubic miles of water (partly in the form of snow) fall yearly upon the lands of the earth. Approximately one-fifth of this tremendous quantity of water is carried by streams into the sea each year. Some idea of the enormous amount of energy developed by these streams may be gained by a statement of the fact that they make an average descent of nearly one-half of a mile, this being the average altitude of the lands of the earth A very considerable amount of energy is also developed by streams of desert regions which do not enter the sea. Much of this stream energy is used up in friction, in wearing away rock materials from the bottoms and sides of their channels, and in transporting sediment.

Fig 124

Effects of rain wash upon slightly consolidated beds. Near Laguna, California (Photo by the author)

Sources of Stream Water. — Rainfall and snowfall constitute the proximate source of almost all stream water A large part of the water of most streams results from the immediate run-off of the rainfall. The amount of such water fluctuates greatly. The melting of snow, especially in the spring in the northern hemisphere, contributes much water to streams. Another source

of supply is glaciers, nearly every one of which has a stream emerging from it. Ponds and lakes commonly feed water into streams. Still another source of stream water is underground water which emerges at the surface in the form of springs This supply tends to fluctuate relatively little, and it is, therefore, an important factor in the regulation and maintenance of stream flow, especially during periods of dry weather. A large river like the Mississippi

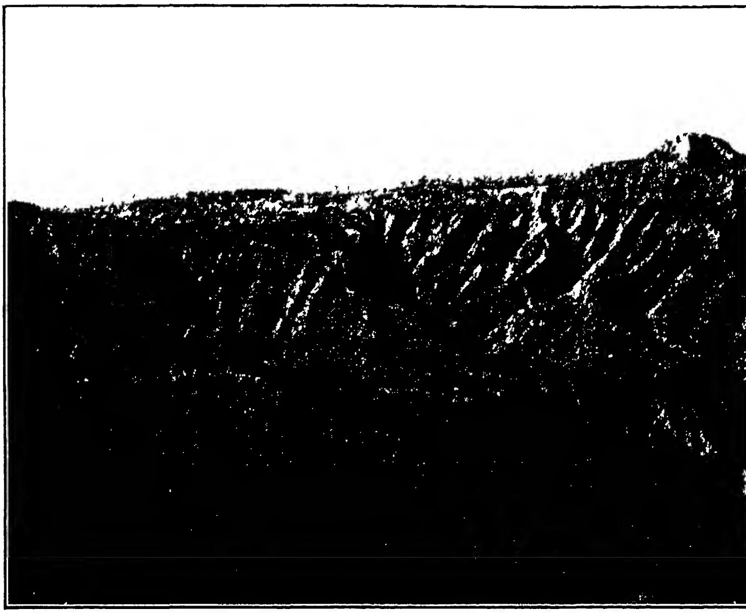

Fig 125

A view in the badlands of South Dakota showing gully development in soft strata. (After Barnett, U S Geological Survey.)

may receive important contributions from all the sources above mentioned.

Rain Wash. — Rain water accomplishes a certain amount of erosion before it collects into definite streams. Everyone is familiar with the fact that soils are carried down slopes by the wash of the rain. When rain " flows off in a sheet, as on a smooth surface, the depth of the water is slight, the flow not very swift (unless the slope is very steep), and the wear correspondingly

slight. Such wear is called *sheet erosion*" (Chamberlin and Salisbury).

Where rain falls upon soft or loose material such as clay or sand, especially where the slopes are steep, the effect of rain wash is much more pronounced than where it falls upon hard rocks (Fig. 124). A mantle of vegetation of course tends to protect soils and rocks against rain wash. For these reasons it is easy to understand why, in regions like New England and the Adirondack Mountains, whose bed rock formations are very hard, and whose soils are mostly stony and resistant, the streams are generally clear except in times of flood, while in regions like the *badlands* of South Dakota, or parts of the western Great Plains, or even parts of the southern states, where not only the soils, but also the bed rock formations, are soft, the streams are very commonly muddy or turbid.

Fig. 126

Erosion and gully development in soft, uniform shales Near Eagle, Colorado. (Photo by the author)

How Streams Erode

Erosion is, as we have already learned, a rather complicated process carried on by either water, wind, or ice, and it consists of a number of sub-processes such as weathering, corrasion, solution, pressure, and transportation. Stream erosion involves all of these sub-processes or factors except weathering, which latter has been dealt with in Chapter IV. It is the present purpose to consider corrasion, solution, and pressure as factors of erosion, reserving the fuller discussion of stream transportation for a separate, more important heading just beyond.

Corrasion. — Surfaces of hard rocks are only very slightly worn mechanically by clear water flowing over them. A remarkable case in point is the constant rush of the mighty volume of

clear water over the crest of Niagara Falls. The water is clear because it comes out of Lake Erie which acts as a settling basin for sediment. In spite of the velocity of the water, myriads of tiny, growing plants (algae) are attached to the rocks at the very brink of the falls, proving that any mechanical wearing away of the rocks must be very slight. The same principle is illustrated by many very clear streams with even rather swift currents

Fig. 127

Tools with which a river works. Boulders in the bed of a river at time of low water Near Wells, New York (Photo by the author)

which emerge from lakes, and whose sides and bottoms may be lined with moss or other vegetation.

In cases of streams of at least moderate velocity and properly supplied with tools, mechanical erosion becomes very pronounced. The tools are rock fragments of all sizes from those of silt, mud, or sand to pebbles or even boulders. By *corrasion* is meant mechanical wearing away of rocks by the rubbing, grinding, and bumping action of rock fragments carried by any agent of transportation — water, wind, or ice — against the bottom and sides of the channel, and also against themselves. We are here con-

cerned with the corrasive action of streams only, corrasion by ice and wind being considered in succeeding chapters

From the above statements it may be readily understood that the factors which facilitate rapid corrasion by streams include swift current, a liberal supply of tools (especially of angular fragments of hard rocks and minerals), and relatively soft or weak rock over which the water flows. Since the tools themselves are worn in the process of corrasion they soon become rounded This is true of all sizes of rock fragments from the tiniest to big boulders.

Solution. — We have already learned that many rocks and minerals are more or less soluble in water, and that their solubility is increased by the presence of small amounts of carbonic acid gas and oxygen which are found in all water in nature. Limestone is, of all the very common rocks, most susceptible to solution, being in fact completely soluble when perfectly pure. Although the process is a slow one as measured by the span of an ordinary human life, nevertheless a stream of even moderate velocity flowing over bed rock of limestone, or even impure limestone, carries away a large amount of the rock in solution in a short time, geologically considered. The cutting of the valley into the crust of the earth is, under such conditions, notably facilitated. Where a stream flows over a hard igneous rock like granite, the work of solution is very much less effective because the quartz in this rock is scarcely, if at all, affected, while some of the feldspar material goes into solution only very slowly As a result of rain wash over the ground, and on gully or valley sides, more or less mineral matter is taken into solution and carried into streams. A large river like the Mississippi carries a tremendous amount of

Fig. 128
Bed rock being eroded by a stream at time of low water. Blue Ridge, New York. (Photo by the author)

dissolved mineral matter into the sea each year. This phase of the subject is treated a little beyond in this chapter.

Pressure. — The mere impact or pressure of running water may, under certain conditions, effect a considerable amount of erosion. Thus a stream of relatively clear water, flowing through soft or loose material, may by this process cut back its bank, or push off material from the bottom of the channel. But even where rocks are hard they are very commonly intersected by numerous cracks (so-called *joints*), causing the rocks to be more or less separated into angular blocks. In sedimentary rocks the stratification surfaces are often also a factor in dividing rock masses into blocks. In many places such joint blocks are only loosely attached to the parent ledge, especially where various agencies of weathering have acted along the joint cracks. Many loosely attached joint blocks of this kind are removed by the mere pressure of the current flowing against them.

Transportation. — A process essential to erosion is transportation, for, unless the rock materials which enter streams are carried away, there can be no wearing down of the land (erosion). This important process of erosion is separately considered a little beyond.

Influence of Joints. — Mention has already been made of the influence of joints in aiding streams to push off blocks of rocks from ledges by mere impact of the current. Where running water enters joint cracks in the sides or bottom of a channel, the work of solution is increased because much larger surfaces of rock are exposed to the action In limestone or limy rocks, joint cracks are often so enlarged by solution that the joint blocks become easy prey to the pressure of the current which pushes them away.

The work of corrasion is also made more effective by joints, particularly where they have been enlarged by solution, or by other weathering agencies, because more rock surfaces are then exposed to corrasive action along the bottom and sides of the channel.

Transportation by Streams

The Stream Load: How it is Carried. — All the material carried by a stream constitutes its *load.* The visible load consists of materials carried in suspension and rolled on the bottom, while

the invisible load is the mineral matter carried in solution. What are some of the sources of the visible stream load? This question may be readily answered by following a typical, small, swift stream, especially in time of flood, through its valley for a few miles, or even less. Materials are carried down the valley sides or slopes by rainwash, or by water from melting snow; landslides and avalanches, as well as the slower movement of hillside creep (see p. 77) contribute considerable quantities of rock fragments of all sizes; loose deposits of clay, sand, gravel, and even boulders,

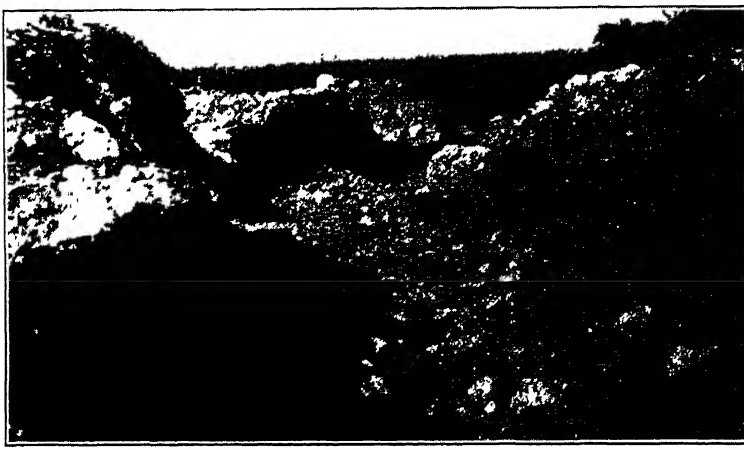

Fig 129
Channel cut by flood waters in about thirty minutes, during 1923. Mouth of Willard Canyon, near Ogden, Utah. (Photo by Robert Nevins)

through which the channel is being cut, easily become part of the load; solid rock of the valley walls, where undercut by the current, falls into the stream; joint blocks of both bottom and sides of the channel may be pushed off by the pressure of the current and become part of the load; and many fragments are supplied by the process of corrasion on the sides and bottom of the channel.

Much of the material in solution (invisible load) is supplied to streams by underground waters where they emerge as springs in the stream valley, some is added as a direct result of the solvent action of rain water on the valley sides; and some is taken into solution by the stream itself from the rocks over which it flows.

The water in a stream does not move as a simple forward current, but rather it is subjected to very complicated motions including the main current forward, upward and downward movements, and "eddies" and "boils." The secondary upward currents bring the finer rock fragments (sediment) into suspension by carrying them up from the bottom of the stream. The coarser, heavier rock fragments are either pushed or rolled along on the bottom of the stream by the current.

Law of Transportation. — Even a moderate increase in the velocity of a stream increases almost incredibly its power to transport rock débris. According to a well-established law of running water, *the transporting power of a current varies as the sixth power of the velocity*. Thus a current which is just able to move a rock mass of a given size will, when its velocity is only doubled, be able to transport a mass of similar rock 64 times as large because 2 raised to the sixth power is 64. This is easily demonstrated in a simple way as follows: A current with a certain velocity can just move along a cubic inch of rock in the form of a cube. Now a cube of rock 64 times as large has 16 square inches on each face. When the velocity of the current is doubled it is evident that twice as many particles of water must strike each of the 16 square-inch surfaces of the larger block with twice the velocity or force. Accordingly, 64 times as much force must be exerted against the face of the larger block, or just enough to push it along. Since the sixth power of 3 is 729 it follows, according to this law, that by trebling the swiftness of the current its transporting power is increased 729 times!

When a stream rises very rapidly during a cloudburst, or when a dam suddenly gives way, the water rushes down a valley with high velocity. An understanding of the remarkable law of transportation helps us to comprehend why, under such circumstances, the water does so much damage, carrying along massive bridges, big boulders, and even locomotives, as happened during the famous Johnstown flood of 1889. It is obvious, therefore, that even streams which are swift at times of low water have their power to transport rock débris greatly increased in times of floods. Not uncommonly a stream will, in a few days of flood, transport more material than in many days or even weeks of low water.

It has been proved that a current with a velocity of only six inches per second can carry along fine sand; one flowing one foot

per second (or about two-thirds of a mile per hour) can move ordinary gravel; four feet per second (or nearly three miles per hour) pebbles weighing about two pounds; and 30 feet per second (or 20 miles per hour) boulders weighing hundreds of tons.

In all of our considerations of stream transportation, it should of course be borne in mind that, due to the buoyant action of water, a mass of average rock with a specific gravity of nearly three looses about one-third of its weight when immersed in water. This greatly facilitates the transporting power of currents.

Graded and Overloaded Streams. — Most streams have sufficient velocity and volume to transport more material than is fed into them from tributary slopes and streams. Such a stream, therefore, has energy left to cut down its channel, that is to *degrade* it. As the down-cutting process goes on, the *gradient* (or declivity) of the stream bed becomes more and more gentle until a condition is reached in which the whole energy of the stream is used up in transportation, and then degradation ceases.

Some streams are unable to transport all the material which is fed into them They are said to be *overloaded.* Not only does such a stream lack power to cut down its channel, but it actually deposits part of its load and so builds up its channel, that is *aggrades* it. As this process of aggradation goes on, the gradient of the building-up channel gradually becomes steeper until a condition is reached in which the whole energy of the stream is used in transportation.

A stream which has reached the balanced condition between downcutting and deposition is said to be at grade. In other words, a *graded* river is one which, on the average, neither degrades nor aggrades, but is just able to carry the load supplied to it from tributary slopes and streams. Due to varying conditions, portions only of a stream may be temporarily graded. Also, a graded stream may degrade its channel during times of flood, while during times of lower water it may deposit, but it is the average condition which should be considered

Amount of Material Transported. — Within the lifetime of a human being, the ordinary river seems to accomplish little or nothing by way of enlarging its valley Within a relatively short part of geologic time, however, a large valley, or even a great canyon, may be carved out (eroded) by a stream. Thus, what is now the space occupied by the whole Connecticut Valley of

western New England was once filled by a mass of solid rock which, during the present (Cenozoic) era of geologic time, has been weathered and eroded, and the resulting materials carried away by the Connecticut River. Or again, the mighty Grand Canyon of Arizona has been formed since the middle of the present era as a result of the removal of a body of rock hundreds of miles long, 8 to 15 miles wide, and thousands of feet thick (Fig. 163). So it is with nearly all of the valleys and canyons of the world because, with relatively few exceptions, they have been carved out by the eroding and transporting power of the streams which they contain. It is, as would be expected, a general rule that the larger valleys are occupied by the larger streams

According to a good estimate, more than 800,000,000 tons of material in suspension, solution, and rolled along are carried annually by the rivers of the United States into the sea Some conception of the amount of this material may be gained from the fact that a train of ordinary freight cars long enough to contain it would reach around the earth at the equator more than six times!

The Mississippi River drains more than one-third of the area of the United States proper. As a result of careful observations and tests it is known that this great river discharges annually about 577,000,000 tons of material into the Gulf of Mexico. About two-thirds of this is material in suspension, about one-fourth is material in solution, and about one-twelfth is rolled or dragged along the bottom. It all represents rock material removed from the Mississippi River drainage basin which covers a million and a quarter square miles. It should be remarked that much of the material in solution is supplied to the river by springs, the waters of which dissolve the material during their underground travels, mostly within a few hundred feet of the surface as explained in Chapter XII. In view of the facts that the Mississippi basin is so vast, and that it includes such a great variety of topography, rocks, and climate, the river which drains it is, in proportion to its size, about an average one as regards the amount of burden carried.

Rate of Erosion

Rate of Erosion of the Mississippi Basin. — All lands are being more or less cut down (eroded) by streams, and estimates

of the rate at which certain rivers are lowering their drainage basins have been made. As a result of measurements and tests near the mouths of these rivers, the load of material carried yearly in suspension, solution, and rolled along by each of them has been determined. Since the burden represents rock material which has been removed from the whole drainage basin of a given stream, and the area of the basin is known, it is easy to calculate how thick a layer of this material of uniform depth would be if spread over the whole basin. The result of course represents the average yearly rate at which the drainage basin is being eroded. Data regarding the Mississippi River are unusually accurate. The area of its drainage basin is 1,265,000 square miles. As a result only of the material carried in suspension and solution, the Mississippi Basin is being lowered at an average rate of one foot in approximately 6120 years (U.S. G S. Water-Supply Paper 234). Considering also the amount of material rolled along the bottom of the river, the drainage basin of the mighty river is being lowered at an average rate of one foot in from 5000 to 5500 years. Although it should be understood that this figure is the result of only an estimate, it is nevertheless probably accurate to within 10 per cent, and thus gives a good idea of the order of magnitude of the rate of erosion by the Mississippi River. In regard to rate of stream erosion, the Mississippi is probably not far from the average for the streams of the world which enter the sea. Some, however, erode much faster, and others much slower. Thus it has been estimated that the Ganges River of India cuts down its drainage basin more than twice as fast as the Mississippi. This is not only because of the much greater average swiftness of the river, but also because of the unusually heavy rainfall over its basin. In the case of the Danube River of Europe the rate of erosion is much less, being one foot in nearly 7000 years.

Rate of Erosion of the United States. — According to estimates made by the Geological Survey, the rivers of the United States transport yearly to tide water 513,000,000 tons of material in suspension, and 270,000,000 tons in solution. Adding the somewhat less accurately known quantity of material rolled along on the bottom, the grand total transported to tide water yearly by the rivers of the United States is considerably more than 800,000,000 tons. If the erosive energy thus expended could have been concentrated upon the Isthmus of Panama, the work of excavation

for the canal would have been accomplished in a little over two months.

All factors considered, and using the best available estimates for the rivers, the surface of the United States is being worn down at the rate of one foot in about 8000 years. This figure is higher than the rate for the Mississippi River because the large area called the Great Basin in the western interior of the country has no drainage outlet whatever to the sea, and other areas like Florida are so low that the average level of the land is either not being lowered, or the rate of erosion is notably less than for the Mississippi Basin.

Time Necessary to Wear Away North America. — The rate at which the continent of North America is being cut down is probably approximately the same as that for the United States, that is one foot in about 8000 years. Since the average height of North America is about 2000 feet it is clear that the streams eroding at their present rate could not cut it down to sea level in less than 16,000,000 years. As a matter of fact, the time required would be much longer than 16,000,000 years for, as the land would gradually become lower, the power of the streams to erode, or, in other words, the rate of erosion, would steadily become less and less. When we realize that large and small portions of continents have been worn down to the condition of plains, or nearly so, during various periods of the known history of the earth, we are forced to conclude that running water has been at work on the face of the earth for many millions of years.

In this general connection the reader should bear in mind that whole continents would seldom if ever be even approximately leveled, because, within such wide areas, constructive forces of diastrophism or volcanic activity would operate to maintain the land.

Valley Development by Streams

Most Valleys Formed by Stream Erosion. — Nearly all streams flow in more or less well-defined valleys. Most of these streams by far flow through valleys which have been carved out by the erosive work of the streams. Some reasons for so believing are that valleys vary in size according to the size of the streams which occupy them, that is the larger the valley the larger the stream in it; tributary streams and valleys are smaller than the ones they

join; a vast majority of tributary valleys and their streams enter larger valleys at accordant levels, that is at the same elevation as the floors of the larger valleys, and many streams, aided by ordinary processes of weathering, are definitely known to be deepening and widening their valleys.

Some valleys were, however, ready-made for the streams which occupy them. These are usually *structural valleys,* so-called because they have been formed by earth-crust movements (*diastrophism*) Some structural valleys, like the Owens Valley in California, and the Jordan Valley in Palestine, each many miles long and thousands of feet deep, were formed by the subsidence (down-faulting) of long, relatively narrow blocks of the earth's crust. Certain others, like the Great Valley of California, were formed by uplift of land into hills or mountains on either side of the valley.

How Stream Valleys Begin. — A new land surface formed in any manner, as for example by the draining of a lake, or by the uplift of land (out of the sea in many cases), soon has a drainage system established upon it. Water from rainfall or melting snow does not flow uniformly over the more or less uneven new surface, but it very soon tends to concentrate in the depressions, and begins to run off in streams. These initial streams begin to carve out *gullies* which, with every fresh supply of water, become deeper, longer, and wider (Fig 125). After a time the gullies are large enough to be called *valleys.* Many gullies may start on a new steep slope, but as time goes on certain of them become wider and take in smaller adjacent ones, and so relatively few of the original gullies really ever become valleys of considerable size.

Not all stream-cut valleys have started their development in the form of gullies. Thus over a great portion of northern North America the vast glacier of the Ice Age (see p. 229) left widespread, irregular accumulations of rock débris over large portions of the area from which it retreated by melting. "Large parts of the surface were left without well-defined valleys, but with numerous lakes (e.g. Wisconsin and Minnesota). The rainfall of the region was enough to make these lakes overflow. Where a lake overflows, the outgoing water follows the lowest line accessible to it, so long as there is a line of descent. In this case, the running water will start to cut a valley all the way from the lake which furnishes the water to the end of the stream at the same time.

No part of such a valley is much older than another." (R. D. Salisbury.) Such a valley is of course not a grown-up gully.

How Valleys Lengthen. — Water which flows into the upper end of a gully or valley cuts back its head by erosion. By such a process of *headward erosion*, a gully or valley is lengthened. A valley head is seldom cut back (lengthened) in a straight line. One reason for this is that differences in the character of the rock material cause headward erosion to proceed more easily in some places than in others. Another is that irregularities of the surface cause the water which flows into the head of the gully or valley to be concentrated first in one position and then in another. For such reasons the headward erosion proceeds irregularly, and thus the crookedness of so many valleys is accounted for.

If a large spring is located at the head of a valley, the dissolving and undermining action of the spring water may aid headward erosion considerably by recession of the spring head.

The lengthening of a valley ends when a permanent *divide* (division of drainage) is developed, because then the amount of erosion on one side of the divide is counterbalanced by that on the other side.

Valley Deepening: Base Level. — A valley is deepened by the cutting down (degradation) of its floor by the erosive action of the stream which flows through it. The excavation of the valley is brought about by all the processes of erosion — weathering, corrasion, solution, pressure, and transportation — which we have already discussed. According to varying conditions, such as swiftness and volume of water, supply of tools, climate, rock character, and rock structure, these different erosive processes operate with varying degrees of effectiveness.

As time goes on, and if no other process intervenes, the power of a stream to cut down (degrade) its valley gradually diminishes, because of lessening velocity, until a limit is reached below which it cannot degrade. The limit is the level of the sea, lake, or valley floor into which the stream empties, but obviously only the lower course of the valley can ever actually reach the limit because there must be at least a slight slope (*gradient*) farther up the valley in order that the stream may continue to flow. The lowest level to which a stream can cut down (degrade) its valley bottom is called *base level.* In this connection it should be remarked that the channel of a stream may be actually a little below the level of the

standing water into which it flows. Thus at and near the mouth of the Mississippi the *channel* of the river is as much as 100 feet below tide water because the current of the mighty river is able to keep its channel scoured to that depth as it rushes into the Gulf of Mexico.

It follows as a corollary to the preceding statements that very deep stream-cut valleys, and the special forms of valleys called

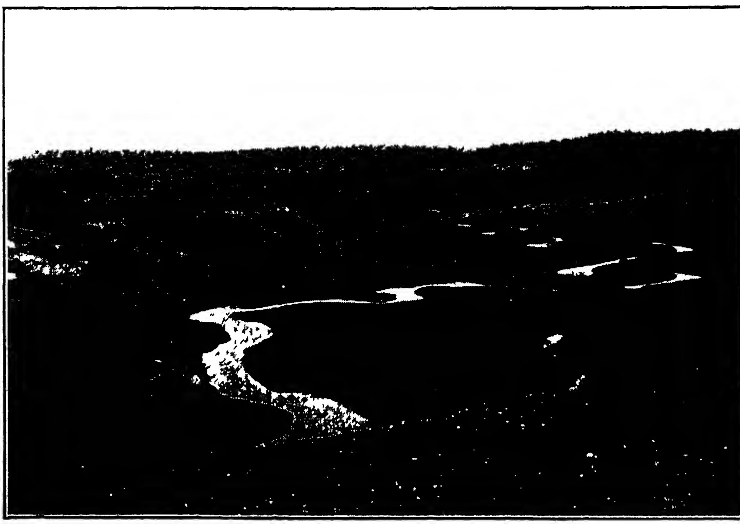

Fig. 130
A meandering stream in a small valley, South Russell, St. Lawrence County, New York. (Photo by the author.)

canyons, can be developed only in lands high above sea level because the higher the land the deeper can a stream erode before approaching base level. This explains why very deep valleys and canyons are found invariably in plateaus and mountains, as for example the Grand Canyon of Arizona in the Colorado Plateau, and the very deep, narrow canyons, such as Yosemite and Kings River, in the Sierra Nevada Range of California

How Valleys Widen. — Most valleys are much wider than the streams which flow through them, but it by no means follows that the streams were ever necessarily wider or larger than they now are. If a valley developed wholly by the down-cutting action of a

stream, the valley would be no wider than the stream, and its walls would be vertical. This latter type of valley (or rather gorge) is approached where all conditions for down-cutting are so favorable that they greatly predominate over other factors which operate to widen the valley. An excellent case in point is the upper end of Zion Canyon, Utah, which is over 2000 feet deep with nearly vertical walls which are in places not more than 100 to 200 feet apart at the top (Fig. 132).

Some of the ways by which the great majority of valleys are made wider across their tops are the following: Loose, weathered materials are washed down the valley sides by rain. If the slopes are steep, some materials roll down, and loose materials especially when they are soaked with water, may *creep* or *slump* to lower levels. On steep slopes, rock material may move down suddenly in the form of *landslides* (Fig. 133). Talus piles accumulate at the bases of very steep valley walls as a result of weathering. Materials which move to the bottoms of valley sides in these and other ways are usually carried away by the streams in the valleys, and thus the tops and sides of valleys which are occupied by actively down-cutting streams steadily become wider. Then, too, since streams are rarely if ever straight, the current in many places strikes one side of the channel with greater force than the other. Thus, while a stream is cutting its channel deeper, it is also doing some direct work of lateral erosion, and so widening its valley at the bottom. Valley widening of this kind is, however, mostly accomplished by streams at or near grade as will next be explained.

Fig. 131
The oxbow of the Connecticut River near Northampton, Massachusetts, formed in 1841. (Photo by the author)

Lateral Erosion: Meanders, Oxbows, and Flood Plains. — Some work of lateral erosion is accomplished by rather actively down-cutting streams, as just explained, but the most effective

work of this kind is done by streams with relatively low velocities and little or no down-cutting power, that is by streams at or near a graded condition Such a stream may flow upon an original nearly flat surface, or in any valley, or portion of a valley, where a graded, or nearly graded, condition has been reached. In a slow-moving stream of this kind, the current is easily turned against one side or the other of its channel. This may be brought about where the swifter current of a tributary enters, or by some obstacle like a rock, or where the material of one bank is more easily eroded than that on the opposite side.

Fig. 132
A very narrow, steep-sided canyon 2000 feet deep The Narrows, Zion Canyon, Utah (Photo by the author)

If for any reason the main current of a slow-moving stream strikes with greater force against one bank, it will be eroded sidewise, and from there the current will be deflected against the opposite bank somewhat farther down stream, causing lateral erosion to take place there. By a continuation of such a process, with the points of attack shifting down stream little by little, a series of sweeping curves called *meanders* develops (Fig. 141). Such meanders become more and more pronounced as a graded condition is approached by the stream, and they finally become a series of loops mostly separated by only narrow necks. Finally the necks are cut through one by one, and cut-off meanders, called *oxbows*, are formed, marking the old channel. Meanwhile other meanders and loops develop.

Wide flats, called *flood-plains* (Fig. 140) because they are

flooded at times of high water, are developed by this process. The lower reaches of some great rivers, as for example the lower Mississippi River, have developed flood plains 20 to 75 miles wide, and hundreds of miles long. Farther and farther upstream the flood plains usually become less and less prominent. Meanders and oxbow lakes are wonderfully developed on large scales for several hundred miles over the flood plain of the lower Mississippi River. The oxbow lakes are there called *bayous*. Oxbow lakes gradually fill with silt and vegetable matter first to form marshes and finally meadow land

Tributary Valleys: River Systems. — In most cases by far a valley has other valleys tributary to it, and these in turn branch

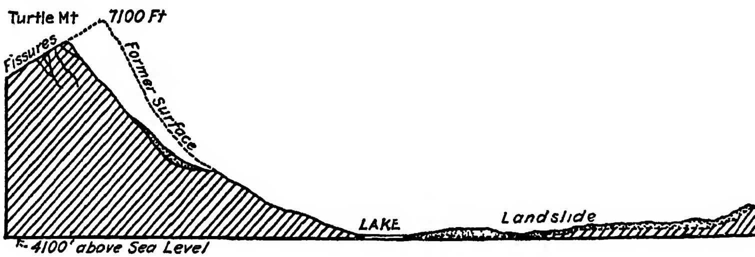

Fig. 133

Structure section illustrating the great landslide at Frank, Alberta, Canada, in 1903 (After McConnell and Brock.)

repeatedly into smaller and smaller tributaries. Tributary valleys usually begin as gullies on the sides of the main valley of a region either where the rocks are of uniform hardness, but where rain water moving down the slopes tends to concentrate somewhat more along certain paths than others, and hence to erode faster there, or where the materials of the slopes are locally weaker and hence more easily eroded A gully once started by such a process develops into a valley on the sides of which other gullies form until, under ordinary conditions, a whole system of branching valleys covers a region A *valley system* thus comprises a main valley with all of its tributary valleys, while a *river system* comprises a main stream and all of its tributary streams. The whole area drained by a river system is called a *drainage basin*.

Accordance of Tributary Valleys. — In normal valley and river systems, it is almost always true that a tributary enters its

parent valley and stream at grade, that is at the same elevation as the main stream. Such streams and valleys are therefore said to be *accordant*. In a river system which is very actively degrading its valleys it might be presumed that tributaries, with their smaller volumes of water, would not be able to cut down the lower ends of their valleys as fast as the main streams into which they flow. The fact is, however, that, as a main stream sinks its channel, the slope or gradient at and near the mouth of the tributary stream is increased enough to enable the latter, through its augmented velocity, to cut down as fast as the main stream in spite of lesser volume.

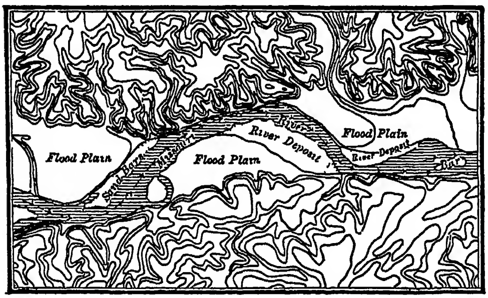

Fig. 134

Sketch map showing an early stage of the meandering of a stream. (From Tarr's New Physical Geography, by permission of the Macmillan Company.)

In cases where main valleys have had their sides (especially toward the bottom) cut back and steepened by glacial erosion, or where they have been interfered with by certain other processes, tributaries may enter main valleys at *discordant* levels.

Stages of Valley History. — When any new land surface of at least moderate altitude is subjected to erosion by streams, the valleys which develop pass through stages of youth, maturity, and old age. These stages show certain characteristics by which they can be recognized.

A *young valley* is narrow and steep-sided because down-cutting has thus far greatly predominated over processes of valley widening (Fig. 147). Tributaries are few in number, short, and not well developed. Streams on high lands which are new soon carve out deep valleys with V-shaped cross-sections. Although on newly exposed low lands with gentle slopes the young valleys are of course shallow, they are, nevertheless, narrow and steep-sided.

A *mature valley* is wider, less steep-sided, and usually deeper than a young valley (Fig. 151). It generally has numerous, relatively large, well-developed tributaries. Well along in maturity a flat begins to develop in the bottom of the valley because the stream in it is approaching grade, which means a steady diminution of down-cutting power, and an increase in its work of lateral erosion.

An *old valley* shows gently sloping sides, moderate to shallow depth, and fewer tributaries than a mature valley. A wide, nearly level floor (flood plain) also characterizes an old valley because down-cutting by its stream has practically ceased, and lateral erosion has developed the broad flats (see p. 160) over which the stream flows in a sweeping, meandering course.

Deposition by Streams

Why Streams Deposit. — It should not be assumed from the preceding discussions that streams are everywhere constantly engaged in cutting down their channels, and so deepening their valleys. Although the great goal of stream work is to wear down the land to near sea level, it is nevertheless true that running water does, under certain conditions, deposit sediment. The transportation of sediment by streams into the sea, or into inland basins, is by no means direct and uninterrupted. Some of the stream load may be temporarily dropped, while some or all of it may be permanently deposited.

The principal cause of stream deposition is diminution of velocity. It is a law of running water that a partial or complete checking of the velocity of a stream loaded with sediment causes deposition of a part or all of its load. Loss of velocity of a stream may be brought about (1) by decrease of slope of the stream bed, especially in the lower parts of a large valley; (2) by a decrease in volume, which always means reduced velocity, as when a stream flows through an arid region where loss by rapid evaporation and sinking into the ground is not counterbalanced by new supplies from springs and tributaries; (3) by a change in the shape of the channel, as when a stream enters a wide, crooked channel just after emerging from a relatively straight, narrow channel; (4) by encountering any obstacle such as a boulder or stranded log in a relatively sluggish stream when a sand-bar or even an island may

begin to develop; (5) by entering a body of standing water when the current is completely checked, and the whole burden of sediment is dropped. Deposition also takes place where a swift tributary carries more sediment into a slow-moving larger stream than the latter can carry.

Alluvial Cones and Fans. — When a swift, sediment-laden stream emerges at the base of a steep slope from a gully, gorge, canyon, or even ordinary valley upon a more nearly level lowland,

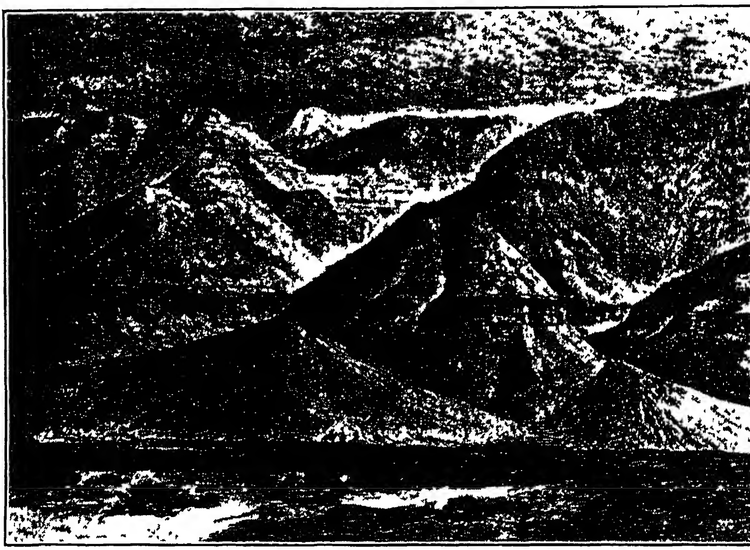

Fig 135

Alluvial cones at mouths of canyons in southern Utah. (After U S Geological Survey)

there is a tendency for the load to deposit at and near the base of the slope. This is mainly because the velocity of the swift stream is suddenly checked. Such an accumulation of rock débris is generally in the shape of a partial cone. It is called an *alluvial cone* when it is steep, and an *alluvial fan* when its angle of slope is relatively low. Cones and fans vary in width from a few feet to a good many miles, and in thickness from a few feet to many hundreds of feet They are grandly displayed in the drier portions of the United States at the bases of mountains, as for example in

Utah (Fig. 135), Nevada, and southern California. An alluvial fan about 40 miles wide has been built by the Merced River where it descends from the Sierra Nevada Range upon the nearly level floor of the Great Valley of California. Where Kings River enters the same valley, there has been such an extensive alluvial fan development across the valley floor that the northward drainage has been blocked enough to pond the waters into a large shallow lake (Lake Tulare).

The shape of the alluvial cone or fan may be explained as follows: At the mouth of the valley of the swift, sediment-laden stream the check in velocity causes deposition of some of the load in the channel, thus choking it, and causing some of the water to spread around the obstruction The minor streams in turn become choked. Locally some water breaks over the sides of the channels, and so develops new channels. By many repetitions of these processes, branching channels, known as *distributaries*, are formed. Much of the deposition takes place at the mouth of the valley or canyon, and directly in front of it, but considerable portions of the sediment spread out on either side, and so the cone or fan-shaped form is developed. A factor which greatly aids the accumulation of the deposit, especially after a cone or fan has been well started, is decrease in volume of water, and hence in carrying power, because so much of the water sinks into the porous fan material.

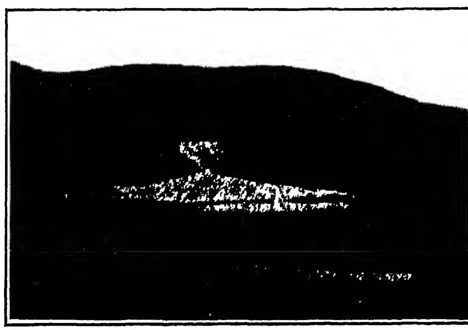

Fig. 136

A small alluvial cone at the end of a gully. North Creek, New York. (Photo by the author)

Piedmont alluvial plains are made by the coalescence of two or more alluvial fans which are built up by neighboring streams. They are really compound alluvial fans. Wonderful illustrations of them are at the foot of the mountains between Pasadena and Redlands in California where they are largely covered with many miles of orange groves. In Colorado, Wyoming, and Montana,

the rivers which flow eastward out of the Rocky Mountains have developed coalescing alluvial fans into a practically continuous sheet several hundred miles long, many miles wide, and not uncommonly hundreds of feet thick, from the base of the very steep Front Range eastward upon the Great Plains. The character and structure of the materials, as well as the fossil remains of land plants and animals in them, prove that the deposits were formed on land through the agency of water.

Alluvial cones and fans are most conspicuously developed in mountainous regions with arid or semi-arid climate not only because streams in the mountains are in general much better supplied with water than those upon the lower levels, but also because, as is characteristic of the drier regions, the rain storms may not uncommonly be of the nature of downpours or cloudbursts. Such conditions are of course very favorable for the development of alluvial cones and fans. It should not be presumed, however, that alluvial cones and fans are rare in humid regions. In such regions small cones or fans may be seen at the mouths of gullies or small valleys where the soil is very sandy or gravelly, and where much of the sediment-laden water emerging from the gully or valley upon the lowland soaks into the porous material (Fig. 136). The courses of some rivers have been notably obstructed as a result of the building of alluvial fans into them by tributary streams. Such a river is forced to flow around the outer border of the fan, and over to the opposite side of the valley. A good case in point is Lake Peoria in the Illinois River. In Switzerland the river which emerges from the Lauterbrunnen Valley has built an alluvial fan into and across a long, narrow lake, dividing it into two parts, Lake Thun and Lake Brienz.

Fig. 137

A combination talus slope and alluvial cone. Near Lake Louise, Alberta, Canada. (Photo by the author.)

Stream-bed Deposits. — We have already shown how relatively swift tributaries sometimes carry so much material, or such coarse rock fragments, into the bed or channel of a main stream that a partial dam is built across the latter. This is because the current of the main stream is not strong enough to keep the material removed. Such a deposit is really a special type of alluvial fan like that already cited as partially blockading the Illinois River to form Lake Peoria. Where some of the short, very swift tributaries of the Colorado River in the Grand Canyon of Arizona feed such large amounts of coarse rock fragments into the river,

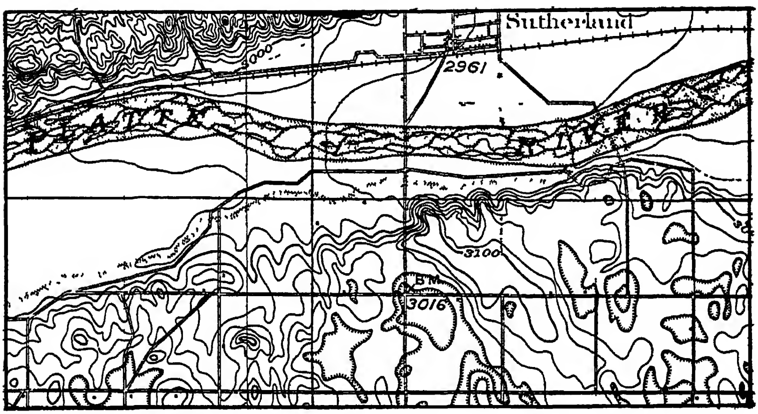

Fig 138

A braided stream. Each square represents a square mile. South Platte River, Sutherland, Nebraska (After U. S Geological Survey.)

the latter, in spite of its swiftness, is not able to remove the fragments fast enough to prevent local ponding of its water.

The current of an ordinary stream is so irregular that while, at a given time, much sediment is being moved down stream, some may be deposited in the back water of eddies, or in portions of the channel where the current is less rapid.

A stream which is carrying a load of sediment during a flooded condition must, as the flood declines, deposit part of its load in the channel because of loss of volume and velocity. Stream-bed deposits formed in the various ways just mentioned are, however, usually only temporary and of very local extent.

Stream-bed deposits assume much greater importance in th cases of streams which, on the average, tend to be overloade and so are forced to deposit much of their sediment. Such stream build up (aggrade) their beds. An excellent illustration of thi principle is the Platte River. Its two main tributaries (North an South Platte) are very swift and, therefore, able to carry unusuall heavy burdens of sediment in times of flood These two tribu taries, as well as the main stream formed by their confluence, los

Fig. 139

Braided channel of an aggrading stream North Platte River on Nebraska Wyoming state line. (After Darton, U S. Geological Survey.)

much of their velocity and considerable volume through evapora tion when they emerge from the mountains, and flow out upor the drier and much more gently sloping Great Plains of Nebraska As a consequence of check in velocity and diminution of volume much deposition takes place, and the river bed is gradually being built up. A considerable portion of the load is more or less movec along during high water, but when the flood subsides extensive deposition takes place.

A stream like the Platte River is an excellent example of a

braided stream, that is one which does not flow in a single definite channel, but rather in a network of ever changing, branching, and reuniting channels (Fig. 138). The local portions of the stream flowing in such channels are called *distributaries*. They are easily explained as follows: When sediment is deposited on the bed of a channel the latter becomes too small to hold all the water, part of which then breaks over the side and flows in a new course. When the new channel becomes sufficiently clogged it in turn develops branches By many repetitions of such a process and the frequent reuniting of channels, the network of courses of a braided stream is produced. The braided course does not exist as such during high water because then the whole flat, which during lower water contains the network of channels, is covered by the stream.

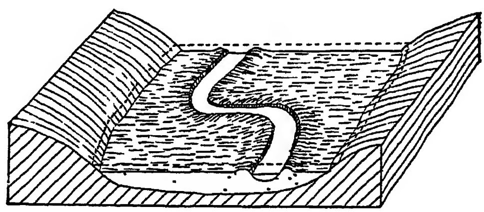

Fig 140
Diagram illustrating river flood plain, deposits, and natural levees Dotted line shows high-water level. (Drawn by the author.)

Gravel or sand bars form in some streams which do not become braided. These are most likely to develop at times of low water. A given bar may be partly or wholly cut away by high water (with increased velocity), or it may last for some time as a low-water island.

Meander Deposits. — When a stream reaches a graded, or approximately graded, condition, and develops meanders, it does so by a twofold process of cut-and-fill. While the current which is directed against the bank of the outer portion of a meander is there performing the work of lateral cutting or erosion, the current is relatively slack on the side of the channel directly opposite, and so deposition takes place there up to flood level On the side where cutting takes place, the bank is steep and the water deepest, while on the opposite (filling) side the bank slopes gently, and the water is shallowest. If it were not for this two-fold process of filling on one side of the channel, and cutting into the opposite bank, the meander could not long continue to develop because cutting alone would widen the channel to such an extent

that the greatly weakened current would lose its power of lateral erosion (Fig. 135).

Flood-plain Deposits. — In most cases by far flats on valley bottoms are developed by the lateral erosion of streams, particularly when they are graded or nearly so. This process has already been explained. In some cases valley-bottom flats are formed by aggradation, as is the case when any land area with its valley subsides so much that enough deposition of sediment must take place in the valley to build up its floor to a graded condition. However they are formed, valley flats subject to overflow during high water are called *flood plains*, defined on page 160.

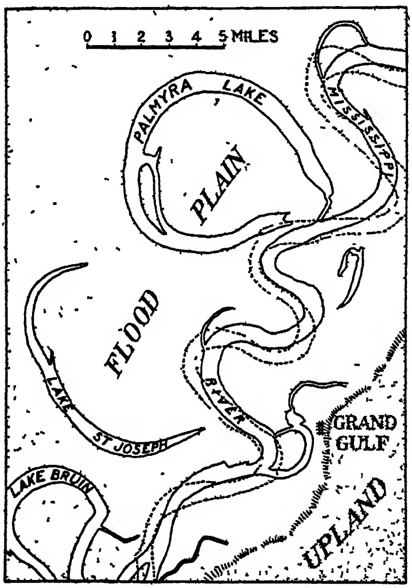

Fig. 141

Meanders and oxbow lakes of part of Mississippi River flood plain in 1883 (heavy lines) and 1896 (dotted lines). (By William Davis, based upon Government Surveys)

When a typical flood plain is covered by high water the current following the main (low water) channel has its velocity greatly augmented so that not only is its power to transport increased, but also it then actually erodes (cuts down) its channel. In the meantime the sediment-laden water over the flood plain has a velocity much less than that of the main current so that some deposition takes place there (Fig. 140) It should not be inferred from this that flood plains always build up very much through deposition because, if a stream is practically graded and the land is not subsiding, the shifting of meanders back and forth all over the flood plain from one side to the other keeps the average level of the plain from changing very much

When muddy water covers the flood plain of a river, the

conditions for deposition are most favorable along the edges of the main channel because there the sediment-laden current of the swift-moving channel water is suddenly greatly checked by friction against the slower moving waters of the flood plain. Because of this sudden diminution of carrying power along the edges of the main channel, more and coarser materials deposit there than over the general flood plain surface. Low ridges of such origin are called *natural levees* (Fig. 140). Such levees can build up only to higher flood levels, and so they cannot, in the course of time, keep high waters from overflowing the flood plain. They are often built up artificially to prevent streams from overflowing their flood plains.

Some Great Floods. — The portion of the lower valley of the great Mississippi River which is subject to floods (i.e , the flood plain) covers an area of about 30,000 square miles It reaches from above the mouth of the Ohio River to the Gulf of Mexico — an air line distance of 600 miles, or about twice that far if measured along the meandering course of the stream. On account of the richness of the alluvial soil many people live on this vast flood plain in spite of the fact that wide portions of it are subject to more or less disastrous floods Thus in 1903 a portion of the flood plain located in the state of Mississippi became inundated, driving 65,000 people from their homes, flooding half the city of Greenville (population 8000), suspending traffic for 20 days, and causing great damage to property. The floods of 1881, 1882, 1884, and 1897 on portions of the Mississippi River flood plain were particularly disastrous, that of 1897 covering thousands of square miles, and causing great inconvenience and a property loss of many millions of dollars to over 50,000 people Worst of all was the great flood of 1912 in the lower Mississippi Valley when the cities of Memphis, Vicksburg and New Orleans all suffered severely Fully 30,000 people were rendered homeless north of Louisiana, and over 100,000 in that state lost much property. It has been estimated that this single flood caused a direct loss of fully $75,000,000 dollars.

The famous Dayton, Ohio, flood of 1913 was caused by five days of heavy rainfall over the Miami and Scioto River Basins, on ground that was already soaked More than 200 towns were more or less inundated, and over 400 people lost their lives Dayton, which is built mainly upon the flood plain of the Miami, suffered most The flood passed over levees more than 20 feet high, and covered much of the city with water 10 feet deep The property damage was about $30,000,000. At the same time great damage was done in the city of Columbus situated on the Scioto River. Although many hundreds of miles of artificial levees have been constructed to more or less effectively control much of the flood water of the Mississippi, nevertheless the river not infrequently breaks through portions of the artificial embankments and floods local portions of the great flood plain.

The famous Passaic River flood of 1902 in northern New Jersey caused damage to the extent of millions of dollars, especially in Passaic and Paterson.

The disastrous Johnstown, Pennsylvania, flood of 1889 was due to the giving way of a dam as a result of heavy rains, and over 2000 people were

drowned The examples given are only a few of the more destructive of the many river floods which have affected various parts of the United States during the last half-century

Probably the most awful river floods of known human history have been those of the Hwang-ho ("China's sorrow") of China The vast flood plain, which is really a delta (see beyond), is 400 miles long and from 100 to 300 miles wide. Its fertile soil has been densely populated for many hundreds of years. A few of the more recent greatest floods took place in 1820, 1858, 1887, and 1892. In each case many villages were wiped away and great numbers of people were drowned One of the most terrible floods was that of 1887 when more than 1,000,000 people lost their lives either through drowning or starvation, and hundreds of villages were destroyed In 1892 the mighty river shifted its course during a flood on the delta flood plain to such an extent that its mouth was about 300 miles farther north after the flood subsided Just before the flood the river emptied into the Yellow Sea (Fig. 142) Ever since the flood it has emptied into the Gulf of Pechili A number of shifts back and forth from the Sea to the Gulf have occurred within the last few thousand years

DELTAS

Cause of Deltas. — Much sediment carried by a stream finally reaches its mouth. If the stream flows into a lake or the ocean, the velocity of the current is largely or wholly checked, and thus much or all of the sediment must be deposited. The destination of most streams is the sea, and, where tides or shore currents in the sea are relatively weak, the discharged sediments accumulate mainly at and near the mouths of the streams in the form of flat, partly submerged, fan-shaped deposits called *deltas*. The name has been given because of the crudely triangular shape similar to the fourth letter of the Greek alphabet If there are strong tides or shore currents in the body of water which the stream enters, or if the amount of sediment discharged by the stream is relatively small, the tendency is either for the sediment to be swept so far away from the mouth of the stream that no delta will form, or only a small or imperfect one will develop. Another reason for the absence of deltas from the mouths of many existing rivers (even some large ones) is the sinking of the land, causing notable submergence of the mouths of the rivers so recently that there has not been time enough for the discharged sediments to build up real delta deposits around the newly located mouths.

Examples of Deltas. — Some examples illustrative of the principles just explained will now be given. Very large and typical deltas have been, and are being, formed where big rivers empty

into certain lakes or nearly enclosed arms of the sea Thus the great Nile River has built into the Mediterranean Sea a very typical delta covering about 10,000 square miles (Fig. 143). The Mississippi River has extended its delta of 12,000 square miles some 200 miles into the Gulf of Mexico (Fig. 144). Extensive deltas have been built by the Danube River into the Black Sea, and by the Volga River into the Caspian Sea. In the face of considerable tidal action, the Hwang-ho River of China has built into the Yellow Sea a vast delta of fully 100,000 square miles (Fig. 142). The combined Ganges and Brahmaputra Rivers of India have, in spite of very considerable tides, formed a delta covering fully 50,000 square miles. The two deltas last named have formed in spite of rather adverse tidal conditions because of the unusually great quantities of sediment discharged by the rivers. Deltas of even moderate size are absent from the Atlantic Coast of North America, not only because of strong tidal action, but also because of notable subsidence of the land very recently (geologically considered) with resultant submergence ("drowning") of the lower portions of the rivers. This is strikingly illustrated by the St. Lawrence and the Hudson Rivers.

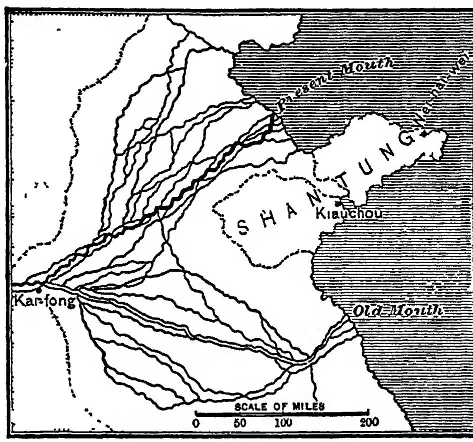

Fig. 142

Delta of the Hwang-ho River, China. (From Tarr's New Physical Geography by permission of the Macmillan Company.)

The Delta Surface. — What are some of the characteristic features of the common type of delta? Its surface is a wide, nearly flat, usually fan-shaped plain mostly a little above, and partly a little below, the level of the body of water into which it grows. Thus about two-thirds of the surface of the Mississippi delta is above water under ordinary conditions, but most of it is

inundated by high water during a flood The great bulk of delta material is, however, always under water, and thus it differs from an alluvial cone or fan whose material is wholly, or largely, on land. Another almost universal feature of a delta surface is the presence of *distributaries*, that is, branches into which the stream splits in increasing number, beginning at the head (upper end) of the delta. These distributaries wander over the delta plain in an ever widening network, and so a delta-forming river always has several or many mouths (Figs 143 and 144).

Delta Structure. — The delta shows a characteristic structure because of the special conditions under which deposition of the sediment takes place. Thus the steep front (Fig. 145), so characteristic of a delta, results from rapid deposition of the coarser sediment layer upon layer where the onrushing sediment-laden stream (or each mouth of the stream) meets the relatively deeper standing water into which the stream flows. These steeply inclined layers are called *fore-set beds* (Fig. 145). They make up the greater bulk of the delta pile. The finer sediments spread out in layers over the floor of the lake or sea to a greater or less distance out from the base of the steep front of the delta. These layers are called the *bottom-set beds.* The earlier formed bottom-set beds of course become buried under the fore-set beds. The *top-set beds* are deposited by the stream on top of the fore-set beds as the latter advance into sea or lake and shoal the water. They build up, for the most part, to a little above the level of sea or lake in layers which slope very gently seaward or lakeward.

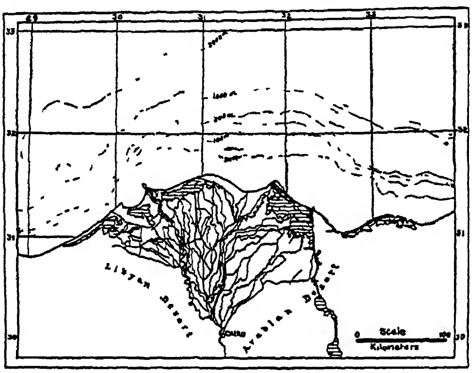

Fig. 143
Delta of the Nile. Depth of water in meters (After J. Barrell).

Rate of Growth of Deltas. — Some rather accurate data regarding the rate of growth of various deltas are known. A few

examples will be mentioned One mouth of the Mississippi Rive is growing into the Gulf of Mexico at the phenomenal rate o one mile in 16 years (Fig. 146). The River Po has extended it delta 14 miles into the Adriatic Sea in 1800 years as proved by

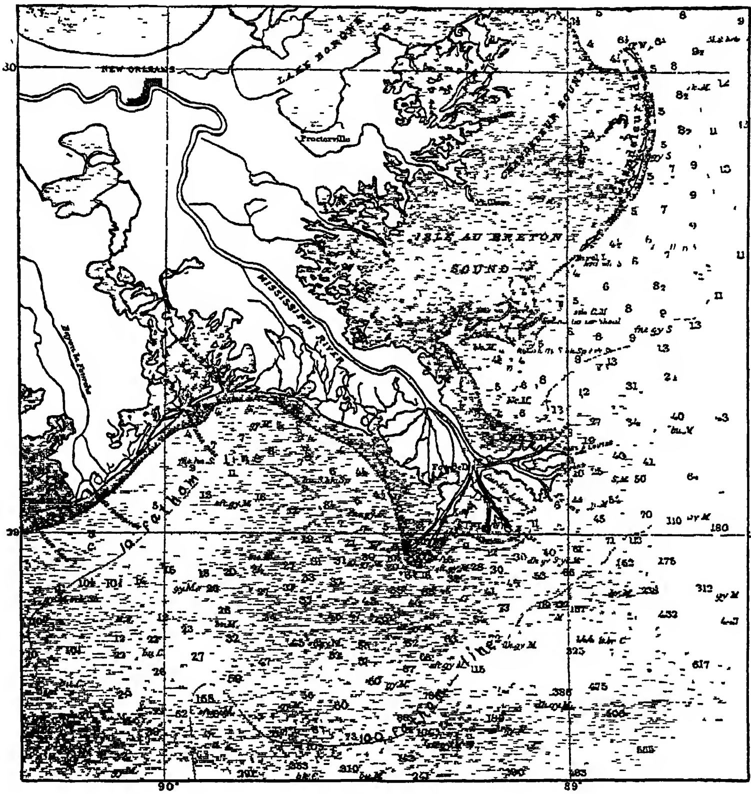

Fig. 144

Map of part of the Mississippi delta about the year 1885. Width of map area, 106 miles. Depth of water in fathoms (After U. S. Coast and Geodetic Survey.)

the fact that Adria, a seaport at the mouth of the river, 1800 years ago, is now 14 miles inland. The Rhone River has been building its delta into the Mediterranean Sea at the rate of one mile in 100 years for many centuries. The ancient seaport of

Rome is now three miles inland because of delta extension by the Tiber River. But by no means do all deltas build out so fast. Thus the great delta of the Nile has grown seaward but little in 2000 years because a current sweeping along the delta front is strong enough to keep the sediment removed about as fast as it is supplied by the river. The Amazon River has not been able to build a delta deposit even up to sea level because of the very strong tides and sea waves, though it has constructed an extensive submarine delta covered by water less than 60 feet deep.

Subsidence of Deltas. — Many of the great deltas of the world have been slowly subsiding while deposition of sediment has been going on. Where the rate of deposition has been somewhat faster than the rate of sinking, typical deltas have developed, but where subsidence has been predominant, even with other conditions

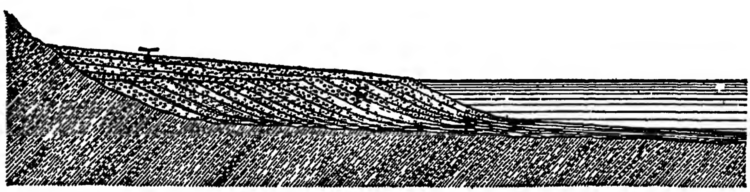

Fig. 145
Ideal structure section of a delta. T = top-set beds; B = bottom-set beds; F = fore-set beds (Modified after G K. Gilbert)

favorable, deltas have not been built up above sea level. Thus the Ganges, Nile, and Mississippi Rivers have built up very extensive deltas in spite of subsidence of fully hundreds of feet. This has been proved by borings into the deposits. By this method "layers of peat, old soils, and forest grounds with the stumps of trees are discovered hundreds of feet below sea level. In the Nile delta some eight layers of coarse gravel were found interbedded with river silts, and in the Ganges delta at Calcutta a boring nearly 500 feet in depth stopped in such a layer" (W. H. Norton). These are of course top-set beds which have, along with the underlying fore-set and bottom-set beds, subsided. Deltas of any consequence are absent from the middle Atlantic coast of North America because of very recent sinking of the land, causing the development of *estuaries* (see p. 190) by flooding of the lower ends of the river valleys with tide water.

History of Stream Courses

Consequent Streams. — On any new land surface, the first streams will have their courses determined by the original slope and natural irregularities of the surface Such stream courses are, therefore, consequent upon the original relief features. They may of course not only lengthen by headward erosion, and deepen and widen their valleys, but they may also have tributaries developed as a direct consequence of the initial topography. All such streams whose courses are the direct consequence of the initial topography are called *consequent streams.*

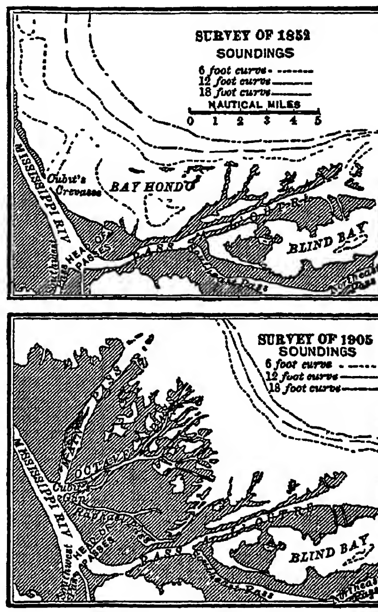

Fig. 146

Maps showing growth of part of the Mississippi delta (After Putnam, from Tarr's New Physical Geography, by permission of the Macmillan Company)

New land surfaces may develop in various ways, some of which will now be very briefly explained. A portion of the sea floor may be raised into land with a relatively smooth surface sloping seaward. Examples are the outer portions of the Atlantic and Gulf Coastal Plains of the United States which are of geologically recent origin. In this region the southern part of Florida is so recent that its consequent drainage is exceedingly young. If a portion of the crust of the earth is newly upraised into a ridge or range by an earth-crust disturbance, consequent streams develop courses down each side of the ridge, as is the case with the Sierra Nevada Range. Where the newly uplifted mass is dome-shaped, or where a new volcanic cone develops, the consequent streams radiate downward in all directions from the summit. Newly built-up lava plateaus,

like those in Yellowstone Park, eastern Washington, or southern Idaho, will have consequent streams developed upon their surfaces. Where new land surfaces result from widespread deposition of materials by glaciers, especially vast glaciers like those of the Ice Age (see page 229), over older land surfaces, consequent streams develop on the new surfaces. Large portions of Iowa and Illinois are good illustrations

Subsequent Streams. — During the history of a drainage system, it happens almost invariably that many stream courses originate independently of the original (initial) topography, and are determined and regulated by erosion proceeding differently upon the bed rock formations according to differences in hardness, structure, and resistance to erosion of the formations. Such streams are said to be *adjusted* because they carve out their valleys along lines or belts of the weaker or more yielding rocks. During the progress of erosion of a region, the divide (division of drainage) between two streams, with courses in rocks of like character, often shifts position notably by headward erosion of the stream with the greater power to erode toward the one with the lesser power, and the upper course of the former stream is not consequent. Also during the history of a drainage system, streams (or portions of them) are not uncommonly captured by (drained off into) other streams, thus bringing about changes in stream courses not consequent upon the original topography of the region.

All streams which develop independently of, and subsequent to, the original relief of a land area, whether by adjustment to rock character or structure, shifting of divides, stream capture, or any other process, are called *subsequent streams* in distinction from consequent streams. Subsequent streams are very commonly tributaries of consequent streams, but even a consequent stream course may, during the progress of erosion of a region, undergo sufficient change to become subsequent. "The original consequent course may, for example, be very irregular and roundabout, and during its development such a course will tend to be straightened. Or the original course may be straight, and, with subsequent development, meandering will be set up. . . . Usually subsequent tributaries develop at (or nearly at) right angles to a consequent master stream. This angular pattern of stream courses is known as *trellis drainage*. . . . Streams in which no adjustment

to rock structure takes place, either (a) because of widespread flat-lying sediments, or (b) because the stream develops in a large area of a massive formation such as granite, never have subsequent tributaries. This is because the adjustment is complete from the beginning. This *insequent* stream pattern is often tree-like, for which reason the drainage is said to be *dendritic*" (Tarr and Martin).

Normal Cycle of Erosion. — *Definitions.* The stages in topographic development through which a region passes comprise what may be called a *cycle of physiographic development* or, perhaps better, *a cycle of erosion* Using a biological analogy, the most important stages of such a cycle have been called *infancy*, *youth*, *maturity*, and *old age*. A cycle of erosion may be defined as "the period of time during which an uplifted (or any new) land mass undergoes its transformations by the processes of land sculpture (erosion), ending in a low featureless plain." These transformations may be relatively simple and easily understood, or they may be very complicated because of wide variations of contributing causes such as climate (especially rainfall), altitude of the land, character and structural relations of the rocks, diastrophic interferences, and others.

Fig. 147

A youthful valley (gorge), with vertical walls, cut in horizontal sandstone beds. Near Mecca, California (Photo by the author.)

By a *normal cycle of erosion* we mean the time required for the reduction to or near base level by erosion (mainly stream action) of a new land area of at least moderate altitude with a humid climate, and with no interfering change of level of the land by earth-crust movements. The principles involved may be best set forth by tracing through the stages in the topographic development of a land mass under the conditions just described, and with

an initial sloping surface reaching to hundreds or even thousands of feet above sea level. Beyond in this chapter, some of the more important variations and interferences with the so-called normal cycle are discussed.

Infancy stage. A typical newly formed land surface, like the kind just pictured, has a drainage system developed upon it. In the earliest stage (*infancy*) of its cycle of erosion, only a few streams form, and these tend to seek out the original depressions, and to flow down the initial slope of the land. These are of course

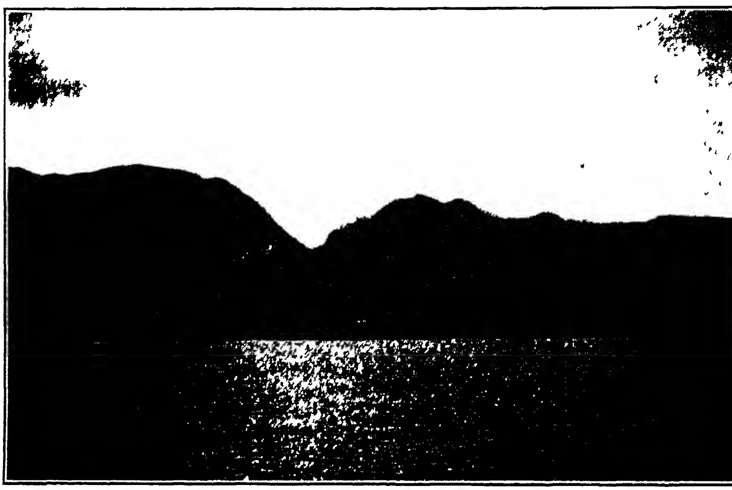

Fig 148

A youthful, V-shaped valley (canyon) several thousand feet deep cut in lava. Island of Maui, Territory of Hawaii. (Photo by the author.)

consequent streams. From the very start some of these streams will be longer, larger in volume, and more energetic as erosive agents than others. A characteristic of all is the small number of tributaries. Not uncommonly some original basin-like irregularities, or depressions, will be filled with water to form ponds or lakes. During infancy, stream erosion accomplishes very little, but the process of sheet erosion (p. 146) is then most effective.

Youthful stage. The region relatively soon passes into the next stage called *youth* (Fig 150). During this stage the streams carve out narrow, very steep-sided valleys usually with V-shaped

cross-sections (Fig. 149). All of the streams are very actively engaged in deepening their valleys by erosion, or in other words, none of them have reached a graded condition. Flood plains and meandering streams are therefore lacking. During this youthful stage, there are few if any sharp divides (divisions of drainage), and the streams are still relatively few in number. The relief of the region is, for most part, not rough. General erosion of the

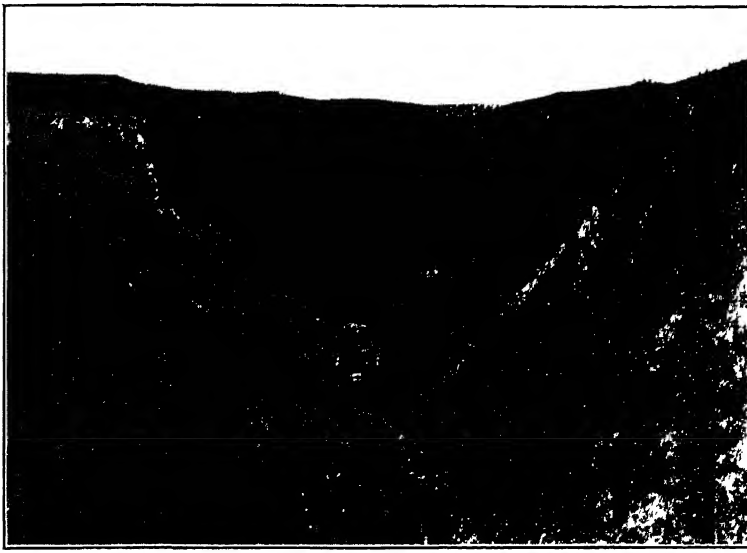

Fig. 149

A youthful V-shaped valley cut in a high plateau of lava. Grand Canyon of the Yellowstone, Yellowstone Park. (After W. T. Lee, U. S. Geological Survey.)

region is not far advanced because erosion is largely confined to the relatively few stream channels. Gorges (or canyons), waterfalls, or lakes (or ponds) are not uncommonly present because they are geologically short-lived features which are indicators either of a youthful topographic stage of a region, or of some geologic process or disturbance which has recently affected a topographically older region, as pointed out beyond. Some examples of regions in topographic youth are much of the Atlantic Coastal Plain of the United States which has recently emerged

from the sea; the Colorado Plateau of Arizona, with its Grand Canyon, which has been geologically recently upraised to its present altitude, and the general vicinity of Fargo, North Dakota, which is part of a large lake bed from which the water has been so recently drained that it is in early youth

Mature stage. Erosion continues until the features so characteristic of youthful topography gradually give way to those distinctive of *maturity* (Fig 150). A region in typical maturity has the maximum number (usually a network) of streams most of which flow in valleys which are wider and less steep-sided than those of youth, that is their cross-sections are broader V-shaped. The maximum roughness of relief has developed (Fig. 314). Divisions of drainage (divides) are well-defined and sharp. General erosion is, in fact, then most effective because practically the whole region has been reduced to slopes. Waterfalls, gorges (or canyons), or lakes (or ponds) rarely if ever exist because time enough has been given for the streams to obliterate such temporary features. Between middle and late maturity one (or more) of the larger streams of the region has cut down near enough to a graded condition (at least in its lower course) to begin meandering with resultant development of a flood plain. During maturity a river system does its maximum work in regard to amount of down-cutting, quantity of water carried off, and load of sediment transported. A very fine illustration of a region in typical maturity is that around Charleston, West Virginia. A wide region around Lancaster in southwestern Wisconsin, including a part of the Mississippi River, is also a good example of maturity. Except for the very recent addition to it here and

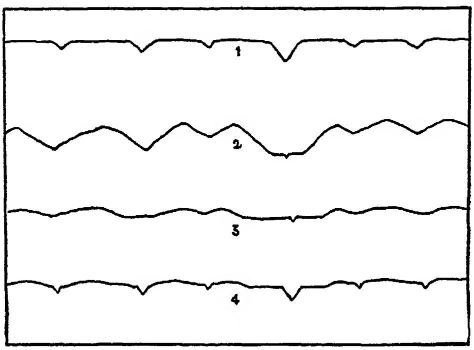

Fig 150

Profile sections illustrating (1) youthful, (2) mature, (3) old age, and (4) rejuvenated stages of topographic development. (Drawn by the author)

there of some minor features of youth, as inheritances of the Ice Age, such as gorges, waterfalls, and ponds, the region of central-western Massachusetts, with its Connecticut Valley, is a fine example of a region in late maturity (Fig. 151).

Old-age stage. As the erosion of the region progresses, the *old-age* stage is reached when the relief has been greatly subdued to the condition of an undulating plain, or so-called "rolling country." Divides are then not at all sharp, being low, rounded hills. Only a moderate number of streams remain, and these flow through wide, shallow valleys. Most of the streams (especially the larger ones) are graded or nearly so, and their sweeping meanders and cut-off meanders (oxbows) on wide flood plains are common and characteristic. General erosion and the amount of work accomplished by the streams are much less than in maturity. Gorges and waterfalls are absent, but oxbow lakes, which are easily distinguished as such, are present. A region well along in the old-age stage of its erosional history has a highly subdued topography of very low relief, which, in the final stage of a perfect cycle of erosion, would be a featureless plain at base level. It is doubtful if any wide area has ever been reduced to such a base-leveled condition, although such a condition has often been rather closely approached. Very typical examples of old-age topography are south-central Kansas in the general vicinity of Caldwell, and the region around Butler, Missouri.

Fig. 151

A region in maturity. Connecticut Valley of Massachusetts. (Howell's relief model, photographed by the author)

Time involved. The terms infancy, youth, maturity, and old

age, as above employed, do not denote anything like definite periods of years, but rather they represent stages, each with certain characteristics, of the cycle of erosion of any given region. Since conditions of altitude, slope, rock character, and rainfall of different regions vary so widely, it is clear that either topographic maturity or old age may, as measured in years, be reached in one region, or even a portion of a single region, long before it is in another. The terms under consideration "have reference not so much to the length of their history in years as to the amount of work which streams have accomplished in comparison with what they have before them."

Peneplains and Monadnocks. — *Definitions.* Any region which has been worn down by erosive agencies to a condition of very low relief at, or nearly at, base level is called a *peneplain* (or peneplane), meaning an "almost-plain." A perfect peneplain would be a plain wholly at base-level-of-erosion, but because probably no large land area has ever been completely base-leveled, it is customary to call a region of faint relief, well along in the old-age stage of its erosion, a peneplain. Perfect base-leveling of a region must rarely if ever take place because, as old age is approached, the rate of erosion becomes slower and slower as the gradients of the streams become less and less, so that the time necessary for perfect planation would be almost infinite. Almost invariably diastrophism, igneous activity, glaciation, or some other process notably affects the region long before anything like a perfect peneplain, or base-leveled condition, is reached.

It often happens that, during the development of old-age (or peneplain) topography, more or less local portions of the region are not cut down to the general peneplain level, either because they consist of more resistant rocks, or because they lie in the midst of relatively wide spaces between larger streams, and so are more favorably situated against erosion. Such a residual mass rising well above the general peneplain level is called a *monadnock*, so named after Mount Monadnock of New Hampshire which rises conspicuously above the now upraised, and partly eroded, peneplain of southern New England.

Existing peneplains. Peneplains, or even reasonably close approximations to them, are not very common over wide areas of North America, as may be inferred from the above discussions. One reason for this is the fact that so many portions of the con-

tinent, including many well worn-down (practically peneplaned) areas, have been more or less uplifted in recent geologic time (Cenozoic era), and subjected to renewed erosion. Much of the large area comprising central-western Missouri, southeastern Kansas, and northeastern Oklahoma has been reduced by erosion to a condition of old-age topography approaching a peneplain, though still lying hundreds of feet above sea level.

Recently upraised peneplains. The vast eastern Canadian region, extending from near the international boundary northward to either side of Hudson Bay, consists of a complex mixture of very old rocks and structures which, after long ages of geologic time, was mostly reduced to a common level of very low altitude. This so-called "Laurentian Peneplain" has since (in the Cenozoic era) been rather unevenly upraised in amounts varying from a few hundred feet to about 2000 feet. In the interior of Labrador, for example, the old, eroded, upraised, peneplain surface is so smooth that variations of level are only a few hundred feet within an area of 200,000 square miles.

It has long been known that most of the eastern United States, where the higher lands such as southern New England, New York, and the northern and central Appalachians are situated, was, during later Mesozoic time, subjected to such widespread and deep erosion that it was all worn down to the condition of a remarkably smooth plain (peneplain) near sea level with slow-moving (graded) streams meandering over its surface. In reference to this great peneplaned area Berkey has said: "The continent stood much lower than now. Portions that are now mountain tops and the crests of ridges were then the constituent parts of the rock floor of the peneplain not much above sea level. . . . The ridges and valleys, the hills, mountains, and gorges of the present were not in existence, except potentially in the hidden differences of hardness or rock structure." In southern New England, and in the eastern Adirondack Mountains of New York, some monadnocks stood out above the peneplain level. Mounts Greylock and Monadnock of southern New England mark the sites of such remnants of erosion (monadnocks). The differential uplift of this vast peneplain to altitudes up to a few thousand feet took place in the present (Cenozoic) era of geologic time. It would carry us too far afield to go into the various proofs for the existence of this once great peneplain. One important

line of evidence may, however, be mentioned, namely, the so-called "even sky-line." Since rocks of many kinds and ages are, with very few exceptions (the monadnocks) all truncated or planed off to a general level as indicated by the "even sky-line," it is impossible to account for such a surface except as an upraised and subsequently partly eroded peneplain (Fig 155).

Interrupted Cycles of Erosion. — *Rejuvenation.* The normal cycle of erosion, which, as we have shown, ends with a peneplain condition, may be interrupted at any stage by other processes. Such processes are so varied, and their effects are often so com-

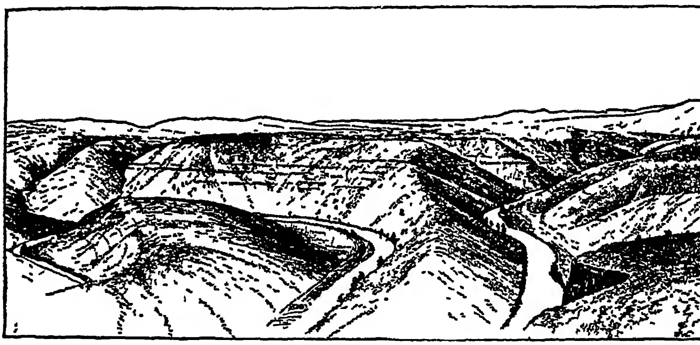

Fig 152

A rejuvenated region showing entrenched meanders Yakima Canyon, Washington. (Hobbs, after G. O Smith)

plicated, that we shall attempt only to explain briefly some of the more important ones and their general effects.

The most common and significant cause of interruption of the normal cycle of erosion is change of level of the land (diastrophism). Thus a region in any stage of its erosional history prior to almost complete peneplanation, say in maturity or early old age, may be upraised with resultant notable increase in velocities of the streams Such a region is said to be *rejuvenated,* and the streams whose activities are quickened are said to be *revived.* The revived streams begin to cut youthful valleys in the bottoms of the wider, older valleys, and thus a new cycle of erosion is inaugurated. The effect is at first most pronounced on the valley floors of the streams which are graded, or nearly so, but in time the whole region is distinctly affected by the revival of erosive activity.

If, through processes of erosion, a meandering stream develops on a flat valley-bottom, and then uplift of the land takes place, the revived stream proceeds to cut a youthful valley in the old valley floor without changing its meandering course. Such meanders are known as *entrenched* (*or incised*) *meanders*. Among numerous excellent examples are the San Juan River of southeastern Utah, Yakima Canyon in Washington (Fig. 152), the

Fig 153

A rejuvenated region showing a youthful valley cut into an older, mature valley Matanuska Valley, near Glacier Point, Alaska. (Photo by Mendenhall, U S. Geological Survey.)

Susquehanna River of southern New York and northern Pennsylvania, and certain rivers of western Germany, Belgium, and northwestern France.

In a case of uplift of a region which has undergone practically complete peneplanation, or base leveling, the general effect is, in nearly all respects, like a new land surface (with consequent streams) formed in other ways, and it may be treated as such. Such a case scarcely comes under the category of an interrupted cycle of erosion.

Rejuvenation by uniform uplift. Rejuvenation may be by uniform uplift of an old eroded surface, in which case the altitude

is increased, but the altitude or slope of the surface is not changed. An excellent case in point is the area of thousands of square miles of central and southwestern New York where many remnants of an upraised, eroded (peneplaned) surface lie at a remarkably even altitude of about 2000 feet, thus indicating a practically uniform uplift of the old eroded surface to its present height. This upraised peneplain has been deeply and widely trenched by erosive processes, including the development of the Mohawk Valley.

Rejuvenation by tilting Tilting (without faulting) may accompany uplift of an old eroded surface This is well illustrated in the case of southern New England where a fairly well-developed

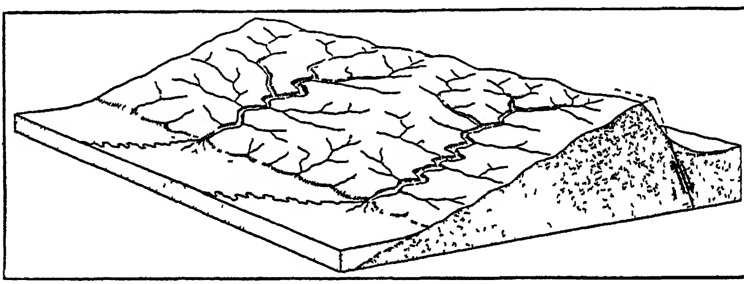

Fig. 154

Diagram representing a portion of the great Sierra Nevada fault-block geologically recently rejuvenated by faulting. (After Matthes, U S Geological Survey)

peneplain was upraised with a distinct tilt southward, as indicated by the slope of the " even sky-line " of the numerous remnants of the old eroded surface. Another illustration is afforded by the great Colorado Plateau of our southwestern states which is an old, approximately peneplaned surface upraised one to two miles, with a southward slope.

Rejuvenation by warping. An erosion surface may be more or less warped during uplift. This principle is finely illustrated by the central Appalachian district. Millions of years ago, the strata were deformed by folding. Then the region was cut down by erosion to an almost perfect peneplain which, in relatively recent geologic time, was distinctly upwarped along a north-south axis, and then deeply dissected by erosion. Plainly preserved remnants

of the upwarped peneplain do not, therefore, rise to a uniform altitude, but they rise steadily higher as the axis of upwarp is approached from both the east and the west sides.

Rejuvenation by faulting. Still another case is the interruption of a cycle of erosion by faulting as wonderfully illustrated by the Sierra Nevada Range of California. The site of the range was once in the topographic condition of late maturity or early old

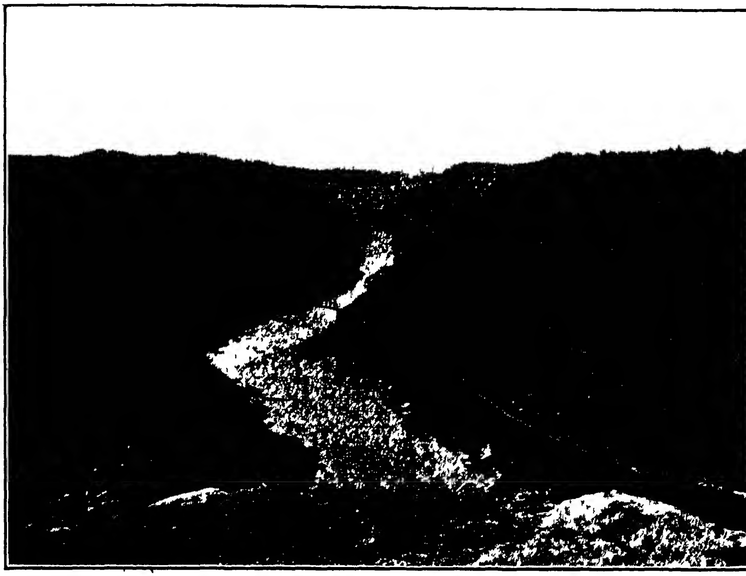

Fig. 155

A valley being cut in the uplifted Appalachian peneplain. Note the even sky line of the mountains. New River, Virginia. (After Hillers, U. S. Geological Survey.)

age, and stream gravels were spread over the old eroded surface in many places. Then a profound fault fracture developed along the eastern side of the district, and the great Sierra earth-block was upraised many thousands of feet, and tilted at the same time towards the west (Fig. 154). The long, wide, western face of the range, therefore, shows a fairly " even sky-line," but by no means a level one for it gradually descends from a summit altitude of 7000 to over 14,000 feet westward, nearly to sea level. Plainly

preserved remnants of the above mentioned stream gravels scattered over the western slope of this vast fault-block range prove that we are here dealing with an old eroded surface uplifted and tilted by faulting.

Cycle interrupted by subsidence. Subsidence of the land also interferes with a normal cycle of erosion. Its general effect is to hasten old age by diminishing the amount of erosive work the streams have to do. Continued sinking causes deposition of sediment in the valleys (or portions of them), thus building up their floors. "If it can be proven that all the graded streams of a region have their beds at levels far above beds which they previously occupied, it seems most likely that the surface of the region has subsided. . . . If uplift raises a previously graded surface above grade, subsidence lowers valley bottoms below the level of grade. This principle seems to be illustrated in the upper Mississippi Valley region, where the Mississippi River and its main tributaries are at grade 100 feet or more above the bed rock beneath" (Trowbridge). The fills in these valleys consist of loose glacial and water-laid sediments.

If a seaboard region in any stage of erosion, particularly from typical youth to typical old age, subsides enough relative to sea level, tidewater floods at least the lower courses of the valleys and their streams, and they are said to be *drowned* (Fig 68). Not only are such valleys, or parts of them, drowned, but also the general erosion of the remaining land is diminished. Such a drowned valley becomes an *estuary,* while the former tributaries of the main stream, now forced to enter tidewater by separate courses, are said to be *dismembered.* The recently sunken coast of Maine is a fine illustration of many drowned-river valleys. The drowned valley of the lower Susquehanna River (Chesapeake Bay), and of the lower Hudson River, are also good examples of such estuaries. The submerged valley of the Hudson has been definitely traced across the sea bottom for fully 100 miles out from New York City (Fig. 67).

Other causes of interrupted cycle. It should not be presumed, from the foregoing statements, that interruptions of the normal cycle of erosion are brought about only by changes of level of the land. Thus the whole northeastern portion of the United States from Minnesota and Iowa to the New England coast was in a topographic condition varying from maturity to early old age

just before the great Ice Age. Then, during and after the recession of the vast glacier (Fig. 193) from the region, extensive deposits of glacial and post-glacial rock débris were left more or less irregularly strewn over much of the surface, giving rise to many low hills, lake basins, and altered drainage courses which latter have not uncommonly developed gorges and waterfalls. Thus many distinct features of a youthful topography are, as a result of glaciation, superimposed upon a large land area which was otherwise well along in its erosional history.

Extensive outpourings of lava may profoundly interrupt the normal cycle of erosion of a region as is so well exemplified on a grand scale in the Columbia Plateau stretching from the Yellowstone Park region westward across Idaho and into eastern Oregon and Washington. The old erosion surface with its stream systems was almost completely buried under the thick accumulations of lava, and new stream courses have been established upon the newer surface of the lava fields.

Arid Cycle of Erosion. — *Streams of arid regions.* The cycle of erosion under arid climate conditions shows certain characteristic differences from the normal cycle in humid regions. Rainfall and, therefore, vegetation are scant. An arid-climate characteristic is that the rain which does fall is likely to be concentrated in a few downpours, each of very short duration, in the course of a year, or possibly several years. Large trunk streams seldom if ever develop. A few only of the stronger streams flow the year round, and most of their tributaries contain water only during, and shortly after, the rare periods of rain. The valleys of the perennial streams are, therefore, nearly always much larger in proportion to the average volume of water flowing through them than those of humid regions. It is commonly the case that parts of a stream bed contain water, and other parts do not. It is also characteristic of arid regions that most of the valleys contain no water most of the time. During the rare, short periods of heavy rainfall (sometimes "cloudbursts"), water at high speeds, and in large volumes, rushes through the valleys, but, within a few hours (or days at most), the stream channels (except the few perennial ones) again become dry.

Stages of a typical arid cycle. The arid cycle of erosion is so much influenced by the nature of the original topography of the region that the order of events in a cycle varies considerably. Our

present purpose is to discuss only the more general principles as they would be illustrated in a rather typical region of varied topography, in the form of a basin (or series of basins) with no stream outlet to the sea, and undisturbed by changes of level of the land The so-called Great Basin of Utah, Nevada, and California may be kept in mind as an excellent example. This basin varies in altitude from somewhat below sea level to about two miles above sea level, with many mountain ridges and ranges rising conspicuously above the general level of the great, irregular floor which is separated into many more or less local basins.

A great, typical, desert basin like that just described has, in *infancy* of topographic development, consequent drainage courses established upon the initial surfaces, including the mountain slopes. These streams, which are seldom active except during and after heavy rains, do not become tributary to a perennial trunk river draining the whole great basin or a large part of it, but they flow down upon the floors of the various local basins where they mostly sink away, or evaporate, or in a few cases enter permanent or temporary ("playa") lakes. Most of the streams are, therefore, mere fragments of what, under humid climate conditions, would be a river system with its trunk river and numerous tributaries.

"In the *youth* of the cycle the highlands are slowly eroded, and deposition takes place on the slopes and floor of each basin, diminishing the relief and raising the local base level, a strong contrast to the corresponding stage of the normal cycle in which relief is increased by the excavation of stream valleys. Even in arid regions, however, valleys are cut on the highland slopes, while the basin floor is made nearly level by deposition. This stage is exemplified by the Great Basin and its mountains. Water is the chief agent of erosion and deposition during the period of youth, but the wind is also important in eroding the bare rocks, and in distributing the finer waste, part of which it carries outside of the arid region altogether. Extremely slow as this process of complete removal of the finer débris by the wind undoubtedly is, yet it is the only agency which actually lowers the average altitude of the region, for no water flows out of the area we are considering" (W. B. Scott).

Maturity of the region is reached when the highlands are deeply eroded, and enough of the resulting sediments have been

carried down and deposited on the floors of the original separate basins to cause them to coalesce. "As the coalescence of basins and the integration of stream systems progress, the changes of the local base levels will be fewer and slower, and the obliteration of the uplands, the development of graded piedmont slopes, and the aggradation of the chief basins will be more and more extensive" (W. M. Davis) During maturity the erosive action of the wind becomes relatively more important not only because rainfall

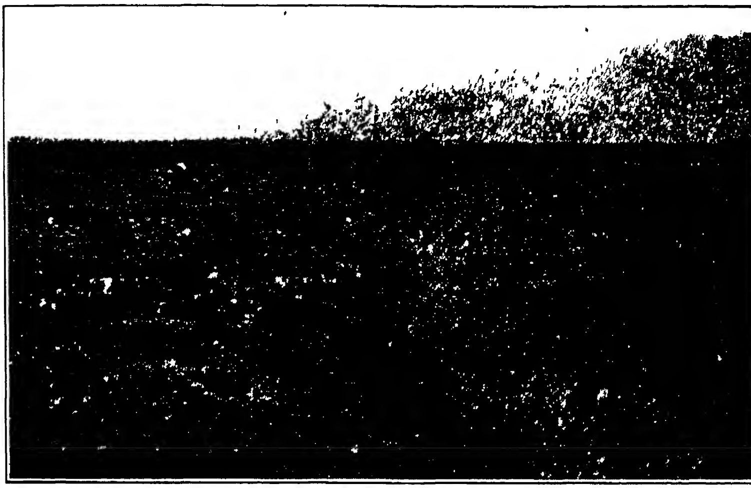

Fig 156

A desert basin being filled with sediment (so-called "wash") carried down from the adjacent mountains. Death Valley, California. (Photo by the author)

is less on the lowered highlands, but also because the swiftness, and hence erosive power, of the streams are much reduced on account of the lower relief.

As *old age* is approached the original highlands are cut down lower and lower, and the now coalesced, local basins are built up more and more until the whole region becomes a wide, nearly flat expanse with broad, gentle undulations consisting of bare-rock plains (truncated highlands) merging into plains of deposition (filled basins). Such a combination plain may be far above sea level. Here and there masses of more resistant rocks may stand

out as residual masses corresponding to monadnocks of the normal cycle of erosion. During late old age in a very dry region the wind is the only very active agent of erosion. By its corrasive power (see p. 267) the wind tends to erode hollows and irregular depressions in the weaker rocks, and to transport some of the sediment past the confines of the arid region, this latter process being of course the only one by which the general level of the old-age plain is reduced.

Stream Deflection. — There is a strong tendency for streams, especially the larger ones whose valleys have not reached old age, to swerve but little from courses once well established Smaller streams, and, much more rarely, larger ones, may, however, be notably deflected from once established courses There are many causes of stream deflection, some of which will now be briefly considered

By rotation of the earth The rotation of the earth on its axis is an appreciable general cause of deflection of streams According to Ferrel's law, "if a body moves in any direction on the earth's surface, there is a deflecting force arising from the earth's rotation which deflects it to the right in the northern hemisphere, but to the left in the southern hemisphere" Streams respond to this law and, therefore, tend to swing against and erode their right banks more than their left, thus causing a general shift of stream courses to the right. Streams flowing north accordingly tend to cut their east banks more than their west banks, and those flowing south their west banks more than their east banks Differences in resistance or structure of the rocks which are being eroded may more than offset this moderate deflective influence. The influence is obviously greatest not only on north or south flowing streams, but also on streams nearer the equator where the speed of the earth's rotation is greater. The streams which flow south across the sloping plain of the southern half of Long Island seem to illustrate the principle. Streams are there cutting shallow valleys into loose, nearly homogeneous sediments with steep banks mostly on the right (west) due to more active erosion there. It has been estimated that the tendency of the Mississippi River to swing against its right (west) bank is about nine per cent greater than toward its left bank

By lava flows. A very simple case of stream deflection may be caused by a lava flow Thus, a stream of lava flowed into and across the channel of the Little Colorado River of Arizona, filling it to such an extent that the river has been forced to find a new course around the lava

By glaciers In a manner very similar to that of a lava flow, a glacier may flow into a valley, forcing the stream over to one side of the valley. Some of the great glaciers of Alaska, as for example certain ones in the Copper River region, are excellent illustrations

The great glacier of the Ice Age filled a portion of the valley of the Columbia River of central Washington, forcing the mighty river to find a new course for many miles, along which it eroded a canyon called the Grand Coulee. On the melting of the ice, the river returned to its former channel.

The Missouri River, which was forced by the great glacier to shift to a

new course many miles farther west in South Dakota, has kept to the new course since the disappearance of the ice (Fig. 157).

By glacial deposits Many streams have been notably deflected from their former courses as a result of the blockading of their valleys by accumulations of glacial materials such as moraines (see page 239). Thus the combined Monongahela and Allegheny Rivers of western Pennsylvania flowed northward into the Lake Erie basin before the Ice Age The old valley was so much filled with glacial débris, which was deposited at the border of the great glacier, that the combined Monongahela and Allegheny waters were forced southwestward into the Ohio Valley.

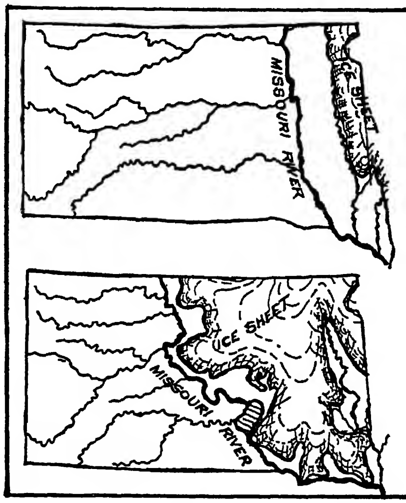

Fig 157

Maps showing how the Missouri River of South Dakota was deflected by the great glacier. (Modified after Todd.)

Another excellent illustration is the lower Sacandaga River of New York which formerly flowed southward into the Mohawk Valley, but now flows northeastward into the upper Hudson River This deflection was caused by heavy accumulations of glacial débris across the old valley near Gloversville during the Ice Age

By wind-blown deposits. Wind-blown materials often cause shifting of stream courses, as for example the Grand Calumet River which once flowed into Lake Michigan in Indiana. Drifting dune sand so blocked its mouth as to reverse the course of the stream which now empties into the lake near Chicago, about 18 miles from its former mouth.

By alluvial cones and landslides. It often happens that rapid building of an alluvial cone or fan on the floor of a valley by a tributary forces the main stream of the valley to flow around the edge of the fan or cone, as illustrated by the Illinois River near Peoria. Landslides also often produce similar effects

By delta growth. Stream deflection on deltas, as well as on alluvial fans, is common, as we have already shown in the explanation of distributaries (p. 165). The Colorado River, which has built a great delta across the upper portion of the Gulf of California, has a usual course into the Gulf, but sometimes it has been deflected down the northern slope of the delta and into Salton Sink.

By levees. Tributary streams, on entering graded or aggrading valleys, are often so deflected by natural levees along the main streams that they flow considerable distances roughly parallel to the main streams before joining them. The junction is usually effected where the main stream swings far over

to the tributary's side of the valley. The Yazoo River of Mississippi is thus deflected for 200 miles before joining the Mississippi at Vicksburg

By log jams. Some interesting cases of stream deflection have been caused by so-called "jams" or "rafts" of trees and logs which have floated downstream. Rafts of this kind have grown to a remarkable extent in the lower course of the Red River in Louisiana, this river below Alexandria having been thus diverted for many miles to a new course nearly at right angles to its old course.

By diastrophism Earth-crust movements (diastrophism) may cause streams to change their courses more or less Large-scale examples of this kind appear to be rare, if not entirely lacking, but the sudden shifting (faulting) of earth blocks (with resultant earthquake shocks) has often caused minor deflections of streams Thus at the time of the great Assam earthquake in India in 1897, movement of earth blocks along a fault fracture parallel to a meandering river caused many local changes in the stream course Also during the earthquakes of 1811–1812 in the New Madrid region of Missouri, many local drainage changes were caused by slipping and tilting of blocks of the earth's crust.

By meandering We have already shown how streams gradually sweep in broad meandering curves back and forth from one side of a valley floor to the other when they are in a graded or nearly graded condition, and how streams abandon such meanders by cutting across their narrow necks (p 160). The great flood plain of the lower 500 miles of the Mississippi River furnishes many fine examples

By stream capture Finally, a very common kind of stream deflection results from the capture of part of one stream by another, and the diversion of the water of the one into the other This interesting and important process of stream development is separately discussed under the next heading

Stream Capture. — *General principles.* During the erosional history of a region it often happens that certain streams steal parts (or all) of other streams by a process known as *stream capture* or *piracy*. The general principle involved is that a stream which finds various conditions for valley development (erosion) more favorable than a near by stream may, by headward extension of itself or one of its branches, tap and divert into itself part (or all) of the stream whose erosional conditions are less favorable. A stream whose upper waters have been captured is said to be *beheaded*. Through the process of stream capture there is a strong tendency for many streams to leave the harder, or more resistant rocks, and develop courses in softer, or less resistant, rocks, that is, they tend to adjust their courses to the character and structure of the various rock formations of a region. This is known as *structural adjustment* of streams.

Examples of stream capture. Some of the more common

principles of stream capture may be made clear by explanation of a few definite cases. Thus, two streams flowing roughly parallel to one another may each develop a tributary reaching out toward the other as shown by Figure 158. Because one of these streams is more active, and has cut its valley deeper, its tributary also cuts down faster, and works headward faster, than the tributary of the other stream. The head of the more active tributary finally reaches the less active tributary and carries off its upper waters. This is a common method of stream capture in many regions.

Where two streams follow approximately parallel courses (one higher than the other) lateral erosion of one or both may at some place completely remove the divide which separates them, causing the stream at the higher level to drain into the lower-level one.

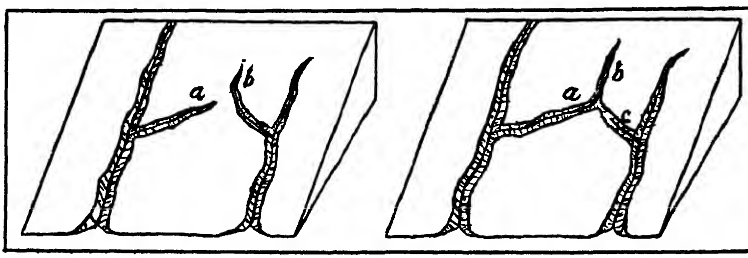

Fig. 158

Diagrams illustrating a simple case of stream capture by headward growth of a tributary. (Modified after Salisbury)

The principle of stream capture by shifting of divides is very clearly illustrated in the Catskill Mountains of New York. As shown in principle by Figure 159, two small, very swift streams (a and b) flow down the steep front of the mountains, while two much less swift streams (b and c) have their courses on the more gradual slope on the opposite side of the divide. The short, swift streams have deepened and extended their valleys headward so rapidly that several branches of the slower streams (b and c) have, one after another, been diverted into the shorter streams. In this case the drainage of the upper waters of streams b and c has been, in the main, reversed, and the original divide has been notably shifted.

The capture of the upper part of Beaverdam Creek by the Shenandoah River of Virginia is a well-known case of stream

piracy. As shown by Figure 160, the Shenandoah developed as a tributary of the Potomac in an early stage of the erosion of the newly uplifted region. Both the Potomac River and Beaverdam Creek cut gorges through the hard rock of Blue Ridge, but the former deepened its valley much faster. The young Shenandoah was, therefore, enabled to extend its course southward by headward erosion, and finally tapped, and diverted into itself, the upper part of the higher level Beaverdam Creek The abandoned channel of the creek across the Blue Ridge is still plainly preserved.

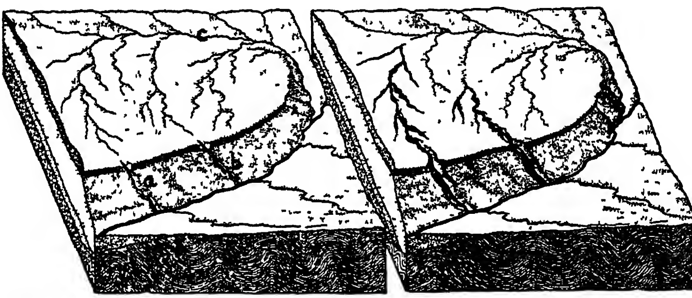

Fig. 159

Diagrams illustrating the principle of stream capture in the Catskill Mountains, New York. (From Tarr and Martin's College Physiography, by permission of the Macmillan Company.)

The short, swift rivers which flow down the western side of the Andes Mountains of Chile have captured the source streams of many of the longer, slower rivers which flow down the eastern side of the mountains and across Argentina.

Antecedent Streams. — A type of river of special interest is one which during, and for a time at least after, disturbance (by diastrophism) of its drainage area maintains the course it had before the disturbance began. Such a stream is said to be *antecedent* because its course was established before the land across which it flows was disturbed by earth-crust movement. The simplest case is that of a revived river resulting from rejuvenation of a region by uplift (see page 187) without much change in the general direction of slope of the land. Thus the rivers of central and western New York have, as already explained, cut valleys in

a rather uniformly upraised peneplain. Since such antecedent rivers merely renew down-cutting along their old courses, it is, perhaps, just as well to call them simply revived rivers.

A remarkable type of antecedent river is one which has kept its course through a rising barrier, even a mountain range. Thus the Columbia River has maintained its course right across the slowly upwarping Cascade Range by cutting a canyon several thousand feet deep while the uplift was in progress (Fig. 161).

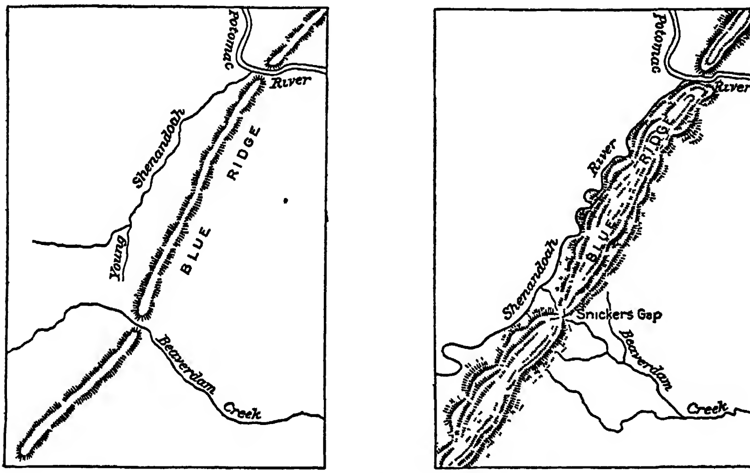

Fig. 160

Sketch maps showing how the upper waters of Beaverdam Creek were captured by the Shenandoah River. (After B. Willis, U. S. Geological Survey.)

If the uplift had gone on faster than the river could erode its channel, the river would have been diverted.

As the Wasatch Range of Utah slowly rose (in recent geologic time) across the path of the Ogden River, the river maintained its course by cutting a deep canyon.

The Indus and Brahmaputra Rivers of northern India are believed to be antecedent, for they cut great canyons through a main range of the Himalayas, and then flow into the Indian Ocean.

Superimposed Streams. — An old land mass with characteristic topography, rock character, and structure may be buried

under later rock formations of very different kinds and arrangement. The newer, overlying accumulations may be sheets of lava, volcanic ash-beds, glacial deposits, lake deposits, or marine strata. The surface of the newer formation may be utterly different from that of the older, underlying formation.

A simple case to consider is a series of gently sloping, nearly smooth strata resting on top of a rugged surface of igneous and

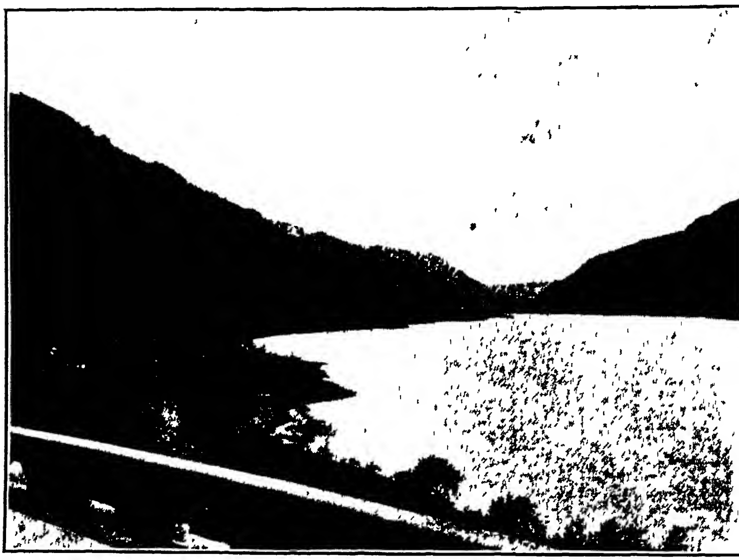

Fig 161

An antecedent river — the Columbia — cutting a canyon across the Cascade Mountains Looking west from Mitchell Point. (Photo copyright by the Weister Company, Portland, Oregon.)

irregularly tilted metamorphic rocks. It not uncommonly happens that a stream, whose course has been determined upon the newer surface, cuts through the overlying rocks and into the underlying rocks, maintaining its course irrespective of the surface, character, and structure of the underlying rocks. Such a stream is said to be *superimposed* or *inherited* (Fig. 162). A fine example is the Colorado River in the Grand Canyon of Arizona where the river has cut through a thickness of several thousand feet of nearly

horizontal strata, and into a very ancient, worn-down, buried mountain area consisting of a complex arrangement of hard igneous and metamorphic rocks In the strata the canyon is wide and terraced, but in the hard, underlying rocks a deep, narrow, steep-walled gorge has been (and is being) cut by the river.

In western Colorado there was once a westerly sloping plateau consisting mainly of a thick accumulation of volcanic ash underneath which was buried an old, uneven-surfaced land mass, including a mountain of granite surrounded by much softer rocks. The Gunnison River started its course on the plateau surface over

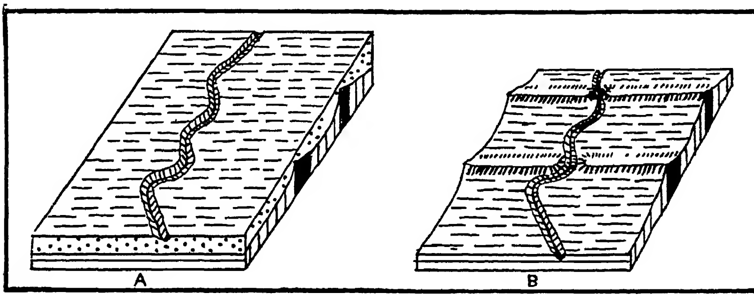

Fig. 162

Diagrams illustrating the development of a superimposed river. (Drawn by the author)

the buried mountain, and, on cutting its valley down to the granite, it was forced to maintain its course, and so cut a canyon 2000 feet deep in the granite. In the meantime the weaker rocks around the granite were largely cut away by erosion. In the light of its history, this apparently paradoxical, present-day course of the Gunnison River is easily understood.

Where, through erosion, the overlying rock mantle has been completely removed from the underlying rocks of different structure, the superimposed streams may have courses very strikingly out of harmony with the structure of the formerly buried rocks. Thus in the Lake District of England a system of streams with a distinctly radial arrangement has been superimposed upon a once buried body of rocks with a northeast-southwest trend. This is a fine example of a superimposed, or *inherited drainage system.*

Special Effects of Stream Work

Canyons and Gorges. — *Definitions.* The principles of ordinary valley development through the agency of stream erosion have already been discussed. We shall now briefly consider the special type of valley which is exceptionally deep in proportion to width. Such relatively deep, narrow, steep-walled valleys are called gorges (e.g. Niagara Gorge), chasms (e.g. Ausable Chasm of New York), dells (e.g. Dells of the Wisconsin), glens (e.g. Watkins Glen of New York), or canyons (e.g. the Grand Canyon of Arizona). The term canyon is generally applied to a large gorge or chasm.

Factors favoring canyon development. Factors particularly favorable to the development of canyons and gorges are rapid down-cutting by streams, and rock formations hard or resistant enough to maintain steep slopes or cliffs when they are cut into. An arid climate is usually more favorable than a moist one because certain weathering agents which cause valley widening are less effective under dry climate conditions. In the development of a gorge or canyon the down-cutting (erosive) action of a stream proceeds so rapidly that the agents of valley widening do not have time to reduce notably the steepness of the valley sides.

Zion Canyon. A remarkable example of a deep, very narrow canyon is the northern portion (so-called "Narrows") of Zion Canyon, Utah, where a very swift, sediment-laden stream under semi-arid conditions has cut its way down into moderately hard rock (sandstone) so fast as to develop a gorge over 2000 feet deep, 20 to 40 feet wide at the bottom, and a few hundred feet (or less) wide across the top (Fig. 132).

Kings River Canyon. A canyon remarkable for its combination of narrowness and depth is the Kings River Canyon of the Sierra Nevada Range of southern California. This steep-sided, V-shaped canyon has been carved out of solid granite by the erosive action of the river, aided by relatively little weathering, to the amazing depth of 6900 feet. Profound uplift and tilting of the Sierra earth-block in recent geologic time; volume and swiftness of the water; hardness of the rock; and a liberal supply of grinding tools are the conditions which have favored the development of this canyon.

Yellowstone Canyon. The Yellowstone River of Yellowstone

National Park has cut a narrow, steep-sided canyon (Fig. 149) over 1000 feet deep and 15 miles long into a high plateau which was built up by outpourings of vast sheets of lava in recent geological time.

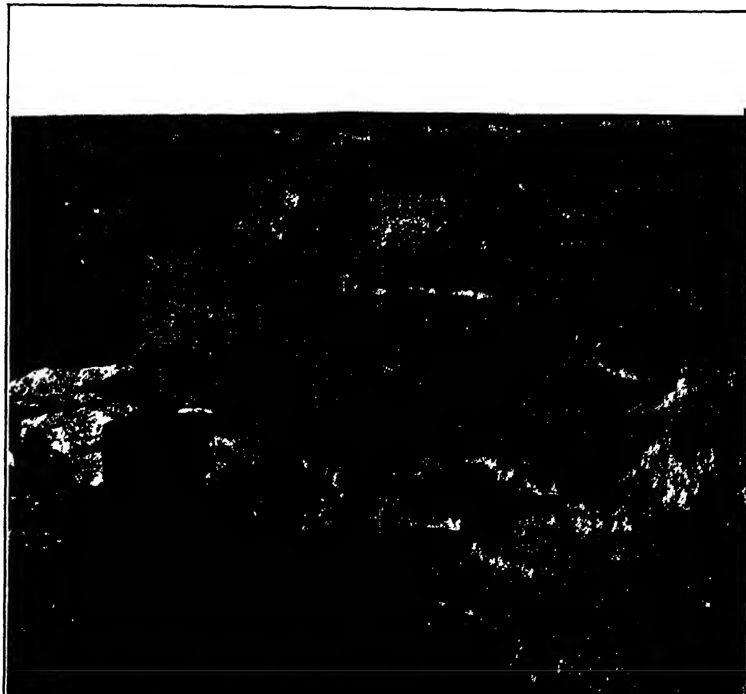

Fig. 163

A view across the world's greatest canyon. Grand Canyon of Arizona (Photo by courtesy of U. S. Reclamation Service.)

The Royal Gorge. The famous Royal Gorge of Colorado has been (and is being) cut through the recently uplifted Front Range of the Rocky Mountains. It is remarkably narrow with almost vertical walls rising to a height of 1500 feet.

Grand Canyon of Arizona. Greatest of all canyons, not only of North America but also of the world, is the Grand Canyon of the Colorado River in Arizona. Its general dimensions are:

length, over 200 miles; depth from 4000 to 6000 feet; and width from 7 to 15 miles (Fig. 163). This mighty gash in the earth's crust has been excavated wholly by the Colorado River and some of its shorter tributaries, aided by weathering. Some of the conditions exceptionally favorable to this canyon development have been and are: (1) The recent great uplift of the region, providing a thickness of many thousands of feet of rocks to be

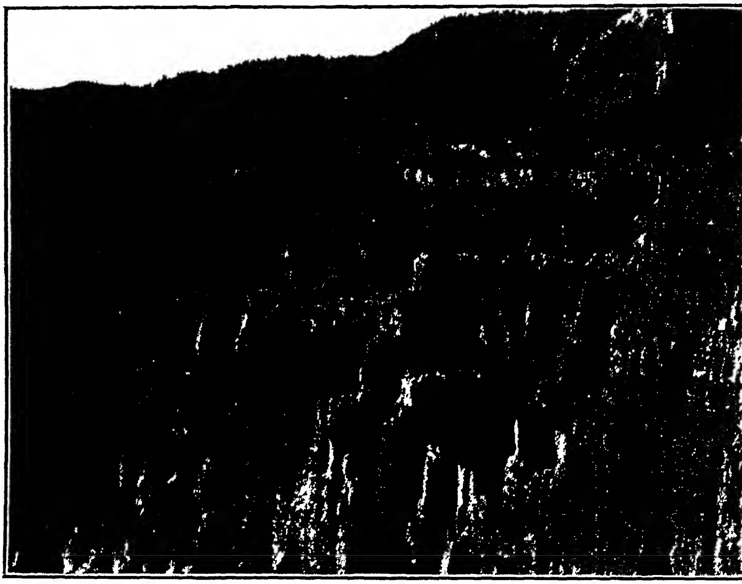

Fig. 164

A detail view in Bryce Canyon, Utah, showing remarkable sculpturing of horizontal strata. (Photo by courtesy of U. S. Reclamation Service)

cut through by the river before reaching grade; (2) the large, very swift river; (3) the abundance of rock fragments constantly carried by the river, thus providing for continually aggressive corrasive action; (4) rock formations hard enough and so arranged that most of them are capable of standing in cliffs or steep slopes; and (5) the arid climate which causes valley widening to be relatively slow.

Canyons modified by glaciers. Many deep canyons in the mountains of the western United States, western Canada, and

southern Alaska are not wholly the work of running water. Such canyons were cut to great depths by streams after which (during the Ice Age) they were occupied for many years by streams of ice called glaciers which deepened and broadened the bottoms and steepened the sides of the canyons. Excellent examples are the Swiftcurrent Canyon of Glacier Park, Montana (Fig. 205), and the famous Yosemite Valley (or Canyon) of California (Fig. 206).

Examples of gorges. There are numerous examples of gorges and small canyons in the eastern United States, such as the Ausable Chasm near Plattsburg, New York, and Watkins Glen of southern New York, each of which is from 20 to 50 feet wide, and 100 to 200 feet deep; the Flume in the White Mountains of New Hampshire; and the gorges of Tullulah River in Georgia, and the French Broad River in North Carolina, each of which is many hundreds of feet deep.

Narrows and Gaps. — River narrows and water gaps are in reality only special types of gorges or canyons. When, during the process of its valley development, a stream takes its course across a belt, or irregular mass, of rock which is relatively more resistant, the valley is there carved out less widely and rapidly than in the weaker rocks just upstream and downstream from the harder rock. Local contractions of river valleys, formed under such conditions are called *narrows*, or *watergaps* if they are very short. Rapids, cascades, and low waterfalls are common in river narrows and gaps. The more resistant rock athwart the channel locally slows up the process of down-cutting, and so there is a tendency for a "temporary base-level-of-erosion" to be established for a greater or less distance upstream from the harder rock.

A few of the many well-known examples of river narrows and water gaps will be cited. The Mohawk River at Little Falls, New York, flows for nearly two miles through a narrow, steep-sided gorge hundreds of feet deep in hard rocks, while for many miles above and below the narrows the valley has been opened out widely on weak rocks (mostly shales). The lower Hudson River has cut a narrows hundreds of feet deep, and 16 miles long, through hard granite and related rocks. Near Northampton, Massachusetts, the Connecticut River has eroded a water gap hundreds of feet deep through the Holyoke Range of hard lava, while the broad valley has been opened up by the river in weaker,

stratified rocks both above and below the gap (Fig. 151). The famous Delaware Water Gap has been cut by the Delaware River through a tilted formation of hard conglomerate, on either side of which there are relatively weak strata. The Susquehanna River near Harrisburg, Pennsylvania, flows through a succession of typical water gaps where tilted, resistant, rock formations, with intervening, weak rocks extend across the course of the river.

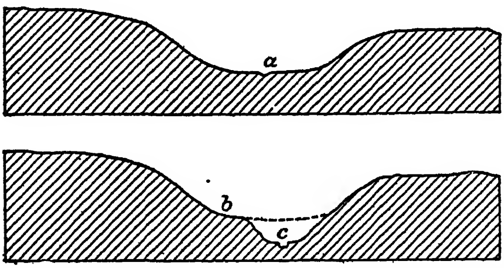

Fig 165
Diagrams illustrating the development of a rock terrace by a stream (After U S. Geological Survey)

A water gap abandoned by its stream becomes a so-called *wind gap* because of the tendency for the wind to blow with unusual force through the narrow opening in the ridge. Wind gaps very commonly result from stream piracy where a stream flowing through a water gap has its course diverted by a neighboring stream. The principle involved is perfectly illustrated in the vicinity of Harper's Ferry, Virginia (Fig. 160), where the water gap of Beaverdam Creek was converted into a wind gap (called Snicker's Gap) because of the capture of the upper waters of the creek by the Shenandoah River. There are numerous wind gaps in the central and southern Appalachian Mountains similar in origin to Snicker's Gap. Many of them are notches in the tops of the mountain ridges. One of particular interest is Cumberland Gap, on the Kentucky-

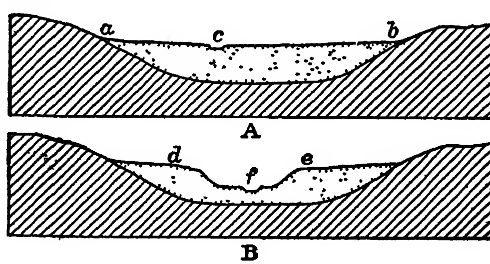

Fig 166
Diagrams illustrating the development of alluvial terraces. (After U S. Geological Survey.)

Virginia line, which is a pass 700 feet deep through the Cumberland Mountain ridge. Several hundred thousand immigrants traveled through this wind gap on their way west in the latter part of the eighteenth century.

Stream Terraces. — Along the sides of a valley there may be benches or nearly flat surfaces with steep fronts facing the stream in the valley, and too high to be covered by flood-waters. Two or more of them may be arranged one above another in steplike form on both sides of the valley. Such benches, when formed by the action of the stream, are called *stream terraces*. Two of their most common modes of origin will now be explained.

Rock terraces. We have already learned that a stream, on approaching grade in its down-cutting process, begins to widen its valley floor notably by meandering back and forth from one side of the valley to the other. A flood plain of such a stream may be covered with more or less stream-deposited (alluvial) soil. Uplift of the region may then take place, causing the revived river to cut a young, steep-sided inner valley (or gorge) into the old flood plain. The remnants of the old valley flat, consisting of bed rock covered with some alluvium, constitute one kind of *rock terraces*. An interesting case is illustrated by Figure 165. After a flat is developed in the bottom of the newer valley, another uplift would inaugurate the development of terraces at a still lower level. Rock terraces also not uncommonly develop during the down-cutting of a valley where resistant layers of horizontal, or nearly horizontal, rocks are worn back on the valley sides less rapidly than weaker layers just above them. A wonderful succession of such rock terraces occurs on a magnificent scale in the Grand Canyon of Arizona, giving rise to what may be called *step topography*.

Fig. 167

Stream-cut terraces in Fraser River valley near Lilloet, British Columbia. (Photo by Calvin)

Alluvial terraces. If, for any reason, a valley becomes partly

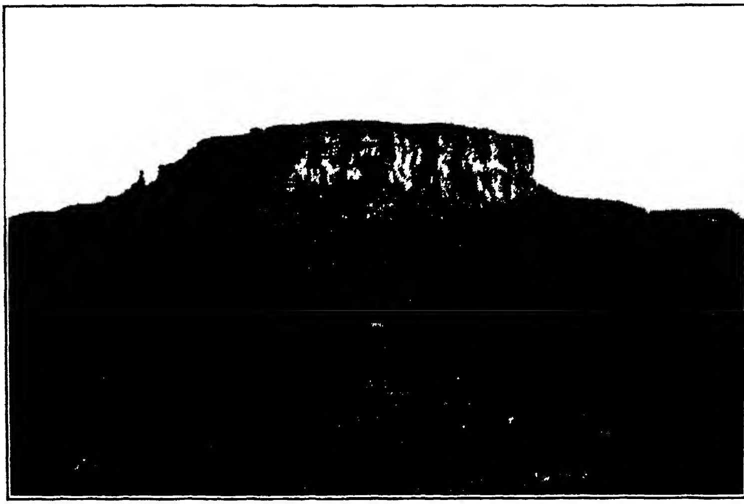

Fig. 168
A mesa carved out of horizontal strata. Near Zuni, New Mexico. (After Darton, U. S Geological Survev.)

Fig. 169
A hogback of Mesozoic strata. Near Fort Wingate, New Mexico. (Photo by Hillers, U. S. Geological Survey.)

filled with alluvial sediment, and then the stream in the valley has its erosive activity notably revived by either decreased load or uplift of the land, so-called *alluvial terraces* will develop. Rapid down-cutting by the stream may result in only one terrace level. Often, however, the stream cuts down into the alluvial filling slowly enough to allow the development of meanders. The stream then cuts laterally into the alluvium first on one side of the valley and then on the other, in each case leaving a flat with a steep face toward the stream. Swinging back to the opposite side of the valley, this time at a somewhat lower level, a new flat is developed and the earlier (higher level) terrace is partly cut away. By such a process a succession of two or more alluvial terraces may be formed (Fig. 166). Excellent examples occur in the Connecticut Valley of New England, and in many other valleys.

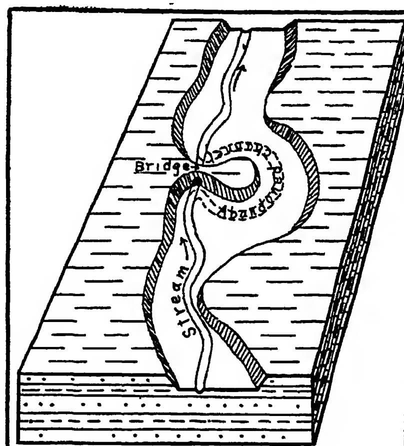

Fig. 170

Diagram illustrating one mode of origin of natural bridges. (Drawn by the author.)

Erosional Remnants. — *General principles.* During the process of general lowering of lands by erosion, it very commonly happens that certain local portions are not cut down as fast as most of the area, and so are left standing out more or less conspicuously above the general level of the country as *remnants of erosion.* There are two important causes of such unequal erosion. One is lack of uniformity of character and structure of the rocks of an area, that is, some portions may be either harder, or more resistant, than others, or less subject to weathering because less broken and fissured by joints or faults. Another cause of erosional remnants is the less rapid erosion in the spaces between streams, this being particularly true in relatively level plain or plateau districts. Erosional remnants are variously shaped and named.

Towers and pinnacles. There may be rock *towers, pinnacles,*

or *pillars* consisting either of notably harder, isolated masses such as the igneous rock of Devil's Tower, Wyoming, or of the cores of volcanoes (volcanic necks) in Arizona (Fig. 271), or of isolated joint blocks of essentially homogeneous material such as the Cathedral Spires in the Garden of the Gods, Colorado (Fig. 54), or the pinnacles and pillars of lava near Douglas, Arizona (Figs. 58, 59, and 60).

Fig 171
The great Augusta Natural Bridge in southeastern Utah (Photo by G L. Bean, courtesy of the National Park Service)

Mesas. If the rocks are in horizontal layers, or nearly so, and some are harder than others, flat-topped hills or small mountains, called *mesas* (pronounced "maysas") often become erosional remnants. In such cases the flat surfaces are determined by harder layers. Similar isolated masses without flat tops are called *buttes* (pronounced " bewts "). Mesas and buttes are common and typical in many portions of the high, arid to simi-arid plains and plateaus of the western United States, particularly the Colorado Plateau of parts of Arizona, New Mexico, Utah, and Colorado

(Fig. 168). Many mesas, buttes, towers, and pinnacles belong in the category of so-called *outliers*, that is, remnants of more extensive bodies of similar rocks separated from the latter by erosion.

Ridges. Where erosion proceeds upon a region of highly inclined to vertical (or folded) rock layers or formations which are alternately hard and soft, the hard belts will, especially during maturity, stand out in relief in the form of *ridges* because erosion cuts down the weaker (softer) rocks more readily, developing

Fig. 172

Niagara Falls. American Fall on the left and Canadian Fall on the right. (Photo by Rau Art Studio, Philadelphia.)

valleys in them. This principle is grandly illustrated by the numerous Appalachian ridges approximately parallel to the mountain range. Very concisely stated, the history of this region is as follows. During Paleozoic time a very thick body of strata (sandstones, shales, and limestones) was deposited layer upon layer on the floor of a sea which overspread the region. About the end of Paleozoic time, the strata were subjected to pressure, thrown into a series of parallel folds, and upraised into a lofty mountain range. Profound erosion then affected the mountains, reducing them to the condition of a peneplain by later

Mesozoic time In early Cenozoic time, the peneplain was upraised and somewhat warped, causing a great revival of stream activity Since this second uplift the present parallel ridges (in harder rocks) and valleys (in softer rocks) have been sculptured out by erosion.

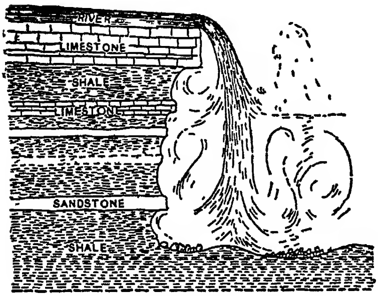

Fig. 173
Structure section at Niagara Falls (After Gilbert, U.S. Geological Survey)

Hogbacks and cuestas. A *hogback* is an erosional ridge with a long, relatively gentle slope on one side and a short, steep (or precipitous) slope or face on the other side. Such a ridge develops where rock layers (or formations) are moderately tilted with a hard layer lying between soft layers. The long gentle slope is caused by the removal of the weak rock from the top of the hard layer, and the tendency of the weak underlying rock to erode (or weather) faster than the hard tilted layer just above it. Hogback ridges, and successions of ridges, are very typically displayed near the eastern base of the Rocky Mountains in Colorado, and also in parts of Arizona and New Mexico (Fig. 169).

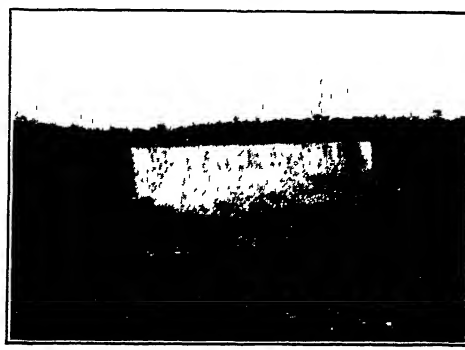

Fig 174
The American Fall at Niagara Falls, New York. (Photo by the author)

A *cuesta* is practically the same in principle as a hogback, but on one side its slope is very long and gentle, while on the other side there is an abrupt slope, or even a cliff. Cuestas are well illustrated in the Atlantic and Gulf Coastal Plains of the United States, and, on a grand scale, in the Colorado Plateau country.

Monadnocks. A special kind of erosional remnant is the

monadnock already described (p. 184). It represents a residual mass of country rock of any shape which has not been reduced to the general level of the peneplain during a late stage in the erosional history of a region

Natural bridges. If, during the process of erosion of a region, a stream perforates the neck of one of its rather deeply intrenched (incised) meanders (see p. 187), a *natural bridge* results, as may be readily understood by examination of Figure 170. The largest natural bridges in the world have originated in this manner, several of them being located in San Juan County, Utah (Fig. 171). Greatest of all is the Rainbow Bridge which would easily span the dome of the Capitol Building in Washington. It should be clearly understood that natural bridges originate in various other ways than by the action of surface streams.

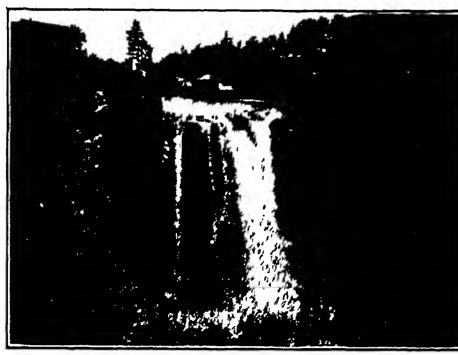

Fig. 175
Snoqualmie Falls, east of Seattle, Washington Height, 272 feet (Photo by the author.)

Waterfalls. — *Definitions.* Where a stream rushes over a steep slope in its bed it forms a *rapid.* Where a stream plunges over a vertical, or nearly vertical, rock face it forms a *waterfall.* Between ordinary rapids and true waterfalls, all gradations exist. Waterfalls are sometimes called *cascades* or *cataracts.* Waterfalls originate in many ways. Our present purpose is to consider only some of the most important principles of waterfall development, with emphasis upon the kinds of falls which owe their existence to the more or less direct erosive action of the streams which themselves form cataracts.

Niagara Falls type. The most common principle is involved in what may be termed the Niagara type of waterfall, so wonderfully illustrated by Niagara Falls (Fig. 172) which is one of the world's very greatest cataracts. Its tremendous volume of water divided into two parts (Canadian Fall and American Fall)

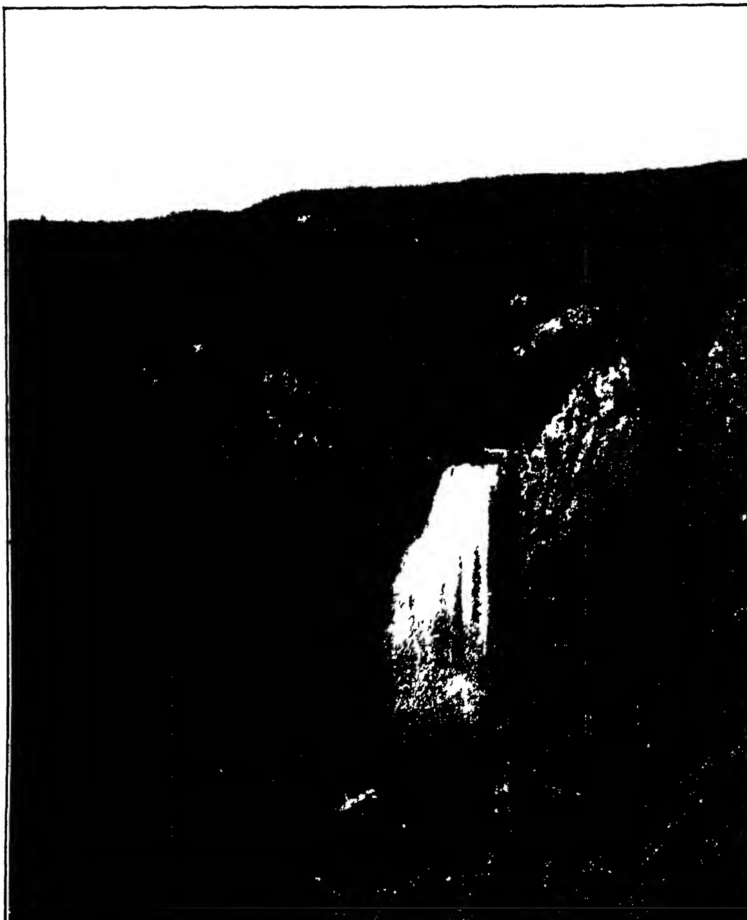

Fig. 176
Great Falls of the Yellowstone River Height, 308 feet. Yellowstone Park. (Photo by F. N. Kneeland)

plunges about 160 feet. In this type of waterfall, the rock formations lie in an approximately horizontal position with a resistant formation on top of a notably weaker one. At Niagara there is a hard limestone resting upon soft shales in thin layers. The con-

ditions are shown by Figure 173. Under the influence of weathering, and the swirling action of the water, the weaker, underlying rocks are cut away faster than the harder overlying rock, causing the latter to overhang so that blocks of it fall down from time to time, and are mostly carried away by the swift current. The waterfall maintains itself while it retreats upstream and develops a gorge By this process Niagara gorge, seven miles in length, has been produced since the withdrawal of the great glacier of the Ice Age from the Niagara region — not more than a few tens of thousands of years ago.

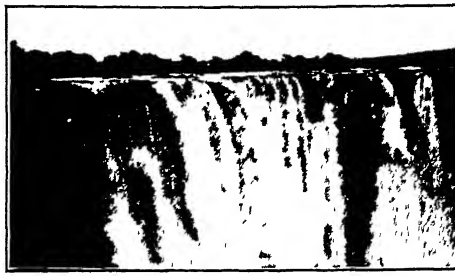

Fig. 177

Detail view of part of Victoria Falls, Zambezi River, South Africa. (Photo by A. J Orner.)

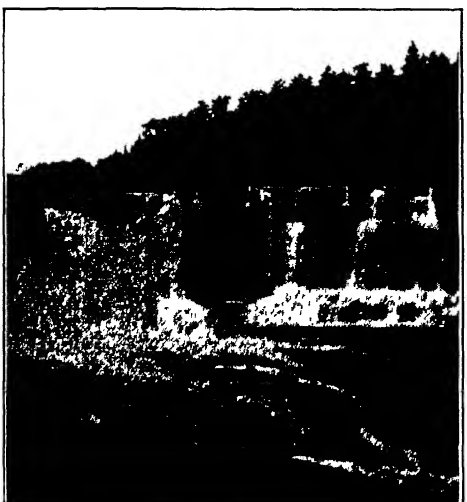

Fig 178

A joint-face type of waterfall. High Falls, at Trenton Falls, New York. (Photo by the author.)

At Snoqualmie Falls (272 feet high) in the Cascade Range of Washington, the rocks are of volcanic origin with a more resistant layer on top of a weaker one (Fig. 175). A layer of hard lava rests upon softer lava at the crest of Shoshone Falls where the Snake River of southern Idaho plunges vertically 210 feet.

Yellowstone Falls type The Yellowstone type of waterfal involves a highly inclined or vertical mass of resistant rock ex

Fig. 179

Yosemite Falls, California. Upper portion, 1430 feet, lower portion, 320 feet (Photo by F. N. Kneeland)

tending across a stream channel, with weaker rock on the downstream (and usually also on the upstream) side of it. At the Great Falls in Yellowstone National Park the river crosses a vertical mass of hard, fresh lava in the midst of other lava which has been much weakened by weathering. This hard rock acts as

a barrier, permitting rapid down-cutting immediately on its downstream side, but checking erosion on its upstream side. The river, therefore, plunges 308 feet over the vertical face of the barrier (Fig. 176). Waterfalls of this kind commonly develop also in youthful stages of erosion in regions with highly inclined or vertical rock formations of varying degrees of hardness.

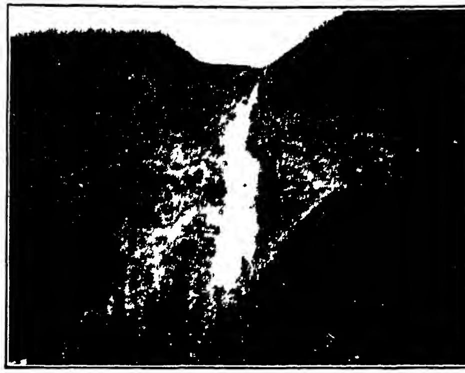

Fig. 180
Takkakaw Falls, Yoho Valley, British Columbia. Height, 1200 feet (Photo by the author.)

Victoria Falls type. The Victoria Falls of South Africa, probably the greatest in the world, involves a principle opposite to that of the Yellowstone type, that is, a belt of weak rock lies across the course of the river in the midst of hard rock (lava). The Zambezi River, finding the work of erosion much easier along the belt of weak (highly jointed and fractured) rock, has turned abruptly to follow the weak rock into which it has cut a deep, narrow chasm. The river, which is here over a mile wide, plunges vertically more than 400 feet into the chasm, which is only a few hundred feet wide (Fig. 177).

Fig. 181
Rainbow Falls, near Hilo, Hawaii, at time of low water. (Photo by the author)

Trenton Falls type. A common type of waterfall results from the removal of joint blocks of rock. Where the rock in the bed of the stream is traversed by well-developed vertical cracks (so-called *joints*), somewhat loosened blocks of

rock may be further freed by weathering, and then one by one pushed away by the stream. In this manner a vertical face of rock is produced over which the water plunges. As such a fall retreats by removal of joint blocks, a gorge develops. Taughannock Falls (215 feet high), north of Ithaca, New York, and several falls (one 50 feet high) at Trenton Falls, New York, are good illustrations (Fig. 178).

Fig 182

A stream bed of limestone honeycombed with potholes Near Boonville, New York. (Photo by the author)

Yosemite Falls type. Another type of waterfall is only indirectly a result of stream erosion. Many of the highest waterfalls of the world belong in this category which we call the Yosemite type on account of the wonderful development of such falls in Yosemite Valley, California. A very active river carved out a deep, steep-sided, V-shaped canyon in the hard granite of the Yosemite region. Then a powerful glacier plowed slowly through the canyon, broadening, and somewhat deepening it, and making its walls precipitous by cutting them back. On the melting of the glacier, various tributaries were forced to enter the main valley by plunging over great granite-cliffs At Yosemite Falls, a stream plunges the amazing distance of 1430 feet vertically over such a granite cliff, this being probably the highest true waterfall in the world. The same water, after descending a very steep slope for 800 feet, plunges 320 feet vertically to the floor of the valley (Fig. 179). Bridalveil Falls in the same valley and of similar origin is 620 feet high. Throughout the mountainous portions of North America and Europe which were occupied by glaciers during

the Ice Age, the Yosemite type of waterfall is common. Examples are a fall 1200 feet high (though not wholly vertical) in the Yoho Valley of British Columbia (Fig. 180), and one 900 feet high in the Lauterbrunnen Valley of Switzerland.

Potholes. — Where rock fragments are given a rapid, swirling motion by an eddy in a swift stream they often wear round or cylindrical excavations, known as *potholes*, in the bed rock of the stream. Such an eddy must of course maintain itself in one place long enough for the grinding action to develop the pothole which may be from a few inches to 25 feet or more in both diameter and depth. As the grinding materials, consisting of sand, gravel, or even boulders, wear out, new materials are supplied by the stream. Local portions of stream beds may be honeycombed with potholes (Fig. 182).

CHAPTER VIII

GLACIERS AND THEIR WORK

Geological Importance of Glaciers

When a body of ice, which has been formed from compacted snow, begins to spread or flow from its place of accumulation it is called a *glacier*. In short, a mass of flowing ice may be called a glacier. Glaciers vary in size from a fraction of a square mile to many hundreds of thousands of square miles.

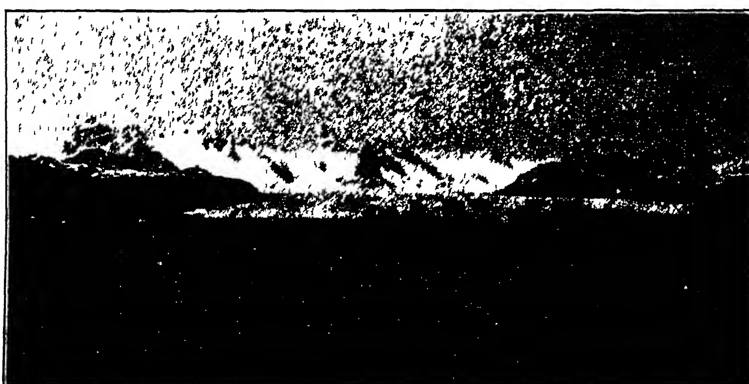

Fig 183
Northwestern Glacier, Alaska, entering tide water. (Photo by U S. Grant for U. S. Geological Survey.)

Much of the land of the earth is, during at least part of the year, covered by snow or ice, and considerable areas are perpetually covered. Moisture, locked up in the form of snow and ice, would tend to accumulate indefinitely in regions of perpetual snow if it were not for the important part played by glaciers in returning much of this moisture to lower and warmer levels.

Glaciers, like rivers, perform their principal geological work by erosion of the land, and by transportation and deposition of rock débris. Although such work accomplished by glaciers is, on the whole, much less than that of streams, it is, nevertheless, of great importance. Streams have been constantly at work upon most of the lands for tens of millions of years, while glaciers have

Fig. 184
Davidson Glacier emerging from a canyon near Skagway, Alaska. (Photo by the author)

been much more restricted both in time and place Water, wind, and ice are the three great agents which operate to modify the lands of the earth by the processes of erosion and deposition.

Types of Glaciers

According to their form, size, and position, we may recognize five types of glaciers as follows: (1) *Valley glaciers*, (2) *hanging glaciers*, (3) *piedmont glaciers*, (4) *ice-caps*, and (5) *continental glaciers*.

Valley Glaciers. — These are often called *alpine glaciers* because of their typical development in the Alps where they were first carefully studied. They are streams of ice flowing through

valleys, and fed from catchment basins of snow located in regions of perpetual snow. They may have tributaries but, as compared to rivers, these are relatively few in number. Of all the types of glaciers, valley glaciers are the most abundant They range in length up to about nine miles in the Alps, and up to 40 or 50 miles in southern Alaska (Fig. 183). Valley glaciers very commonly attain thicknesses of from a few hundred feet to a thousand feet or more, and widths of from one-fourth of a mile to several miles.

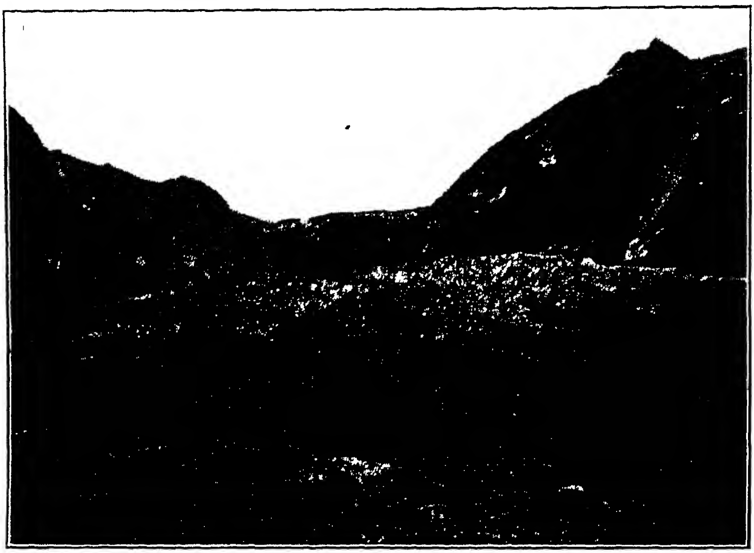

Fig. 185
The lower end of Denver Glacier near Skagway, Alaska
(Photo by the author)

Hanging Glaciers. — These are sometimes called *cliff glaciers*. They are poorly formed, usually small, glaciers which occupy depressions or steep clefts high up on mountainsides and do not descend into valleys. They sometimes move to the edge of a cliff or a very steep slope and break off. Where a glacier of any kind, but especially a hanging glacier, moves to the edge of a cliff or a steep slope and breaks off, the fragments which fall to the base of the slope may freeze together again and form a *reconstructed glacier*. The Lefroy glacier near Lake Louise, British Columbia,

Fig. 186
Hanging glaciers near Lake Chelan in the Cascade Mountains of Washington. (Photo by U. S. Reclamation Service.)

is a good example. There are many fine examples of hanging glaciers in the Rocky Mountains of southern Canada and northern United States, and in the Cascade Mountains of Washington and Oregon (Fig. 186).

Hanging glaciers show all stages of transition to true valley glaciers. Such intermediate types are wonderfully displayed on

Fig. 187
Detail view of a hanging glacier. Glacier National Park (Photo by W C. Alden, U. S. Geological Survey.)

the great volcanic cone of Mt. Rainier, Washington, whose very steep sides support a system of nearly 50 square miles of glaciers (Fig. 188).

Piedmont Glaciers. — A piedmont glacier is formed by the coalescence of the spreading ends of valley glaciers where they flow down mountains and out upon relatively level country. It is, in effect, somewhat like a lake of ice at the foot of a mountain. The Malaspina Glacier, covering 1500 square miles at the foot of the great Mt. St. Elias in northern Alaska, is a fine large example. It has a nearly level surface, and it moves very slowly. Its border portions are almost completely concealed under rock débris and even forest growths. Muir Glacier in Alaska is intermediate in general character between a valley glacier and a piedmont glacier. It covers hundreds of square miles (Fig. 191).

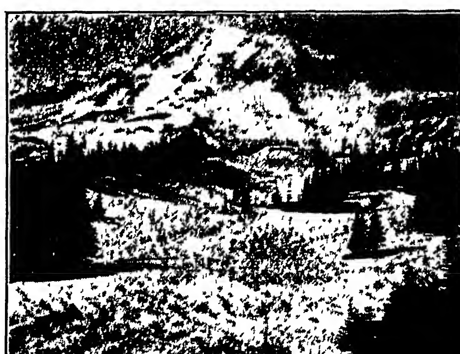

Fig 188
Snow and ice-clad Mt. Rainier, Washington, as seen from near its southern base July, 1921. (Photo by the author)

Ice Caps. — In certain high-latitude regions, such as Scandinavia, Iceland, and Spitzbergen, glacial ice may accumulate on relatively level plains or plateaus as ice sheets which slowly spread or flow radially from their centers. These

are called ice caps. They seldom cover more than a few hundred square miles If properly situated, they may send small alpine glaciers down radiating valleys.

Continental Glaciers. — These are *ice sheets* of great extent, usually covering many thousands of square miles. They are, in principle, much like ice caps, only they are larger. A vast ice sheet now covers fully 500,000 square miles of Greenland, and its motion is outward in all directions toward the sea. It sends off many tongues of ice into the tide water. A still greater ice sheet covers much of the south polar region to an extent of probably at least several million square miles The Greenland and Antarctic ice sheets are the only ones at present large enough to be classed as continental glaciers. In times past, however, still greater expanses of glacial ice are known to have occupied certain portions of the earth, as mentioned beyond in this chapter.

Fig. 189
Looking across Nisqually Glacier on Mt. Rainier, Washington. (Photo by the author.)

Existing Glaciers

Millions of square miles of the earth are covered with glaciers ranging in size from a fraction of a square mile to millions of square miles. Greatest of all are the vast ice sheets, or continental glaciers, occupying much of Greenland and Antarctica Ice caps of less extent occur in the Arctic Islands, Spitzbergen, Iceland, and southern Scandinavia. Piedmont glaciers, like ice caps, are not very common, their best representation being probably in southern Alaska.

Of all the types of glaciers, the valley or alpine type is by far most abundant. They are best known in the Alps where there are probably no less than 2000 of them. Most of them are less

than one or two miles long; a few are from three to five miles long; and one — the Great Aletsch — is over nine miles long. In Europe, the Pyrenees, Carpathian, Caucasus Mountains, and the mountains of Norway also support numerous valley glaciers, those of Norway and the Caucasus being especially large.

The great Himalayas of southern Asia support a magnificent system of very large, high-altitude, valley glaciers, many of them from 5 to 30 miles long. Africa contains few if any glaciers.

The Andes Mountains of South America support many valley glaciers, some small ones at very high altitudes lying practically at the equator. There are many large valley glaciers in the southern Andes.

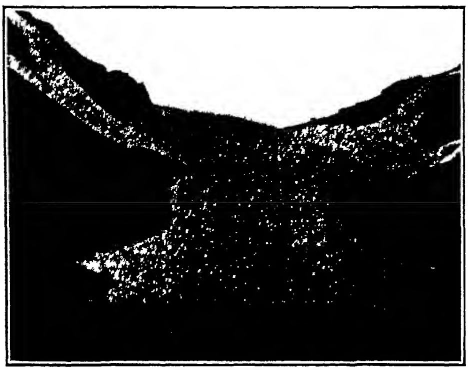

Fig 190

Andrews Glacier, altitude 12,000 feet Rocky Mountain Park. (Photo by W T. Lee, U. S. Geological Survey.)

There are no glaciers in the eastern two-thirds of North America, but the western portion of the continent contains many of them. There are tens of thousands of glaciers in southern Alaska, most of them by far being valley glaciers which range in length up to 50 miles, and in width up to five or six miles. Dozens of them flow down the mountains into tide water where they break off to form icebergs. Southern Alaska is a wonderland of lofty mountains, vast fields of perpetual snow, and numerous, great valley glaciers (Figs. 183 and 194). Valley glaciers of fair size, and hanging glaciers, are common in the southern Canadian Rockies. In the northern Rockies of the United States, from Colorado into Montana, there are scores of small glaciers, mostly of the hanging-glacier type, especially in Glacier National Park. The Cascade Mountains of Washington, Oregon, and northern California, especially the higher peaks such as Mt. Rainier, Glacier Peak, Mt. Hood, Mt. Jefferson, and Mt. Shasta, support numerous glaciers ranging from hanging glaciers to true valley glaciers from a fraction of a mile to five

miles in length Some small hanging glaciers occur in the southern half of the Sierra Nevada Range of California. Certain high peaks of Mexico support small glaciers.

THE GREAT ICE AGE

The Fact of the Ice Age. — The Quaternary is the latest great period of earth history, and it still continues for it has led up to the present-day conditions. This period was ushered in by the

Fig. 191

A general view of the great Muir Glacier, Alaska, showing its terminal cliff (several hundred feet high) in tide water. (Photo by H. F. Reid.)

spreading over much of northern North America and Europe of vast ice sheets which must take rank as one of the most interesting and remarkable occurrences of geological time. During several other periods of geological time, glacial ice was more or less extensively developed, particularly during late Paleozoic time, but the term "Ice Age" refers to that of the present (Quaternary) period. Existing glaciers are but remnants of the once much

greater glaciers of the Ice Age. On first thought the former existence of such vast ice sheets seems unbelievable, but the Ice Age occurred so short a time ago that the records of the event are perfectly clear and conclusive. The Ice Age is estimated to have begun from half a million to a million or more years ago, and to have ended in the northern United States from twenty to thirty thousand years ago.

Some of the proofs of the former presence of the great ice sheet are as follows: (1) polished and striated rock surfaces (Fig. 203) which are precisely like those produced by existing glaciers, and which could not possibly have been produced by any other agency; (2) glacial boulders which are often somewhat rounded and scratched, and which have often been transported many miles from their parent rock ledges (Figs. 220 and 221); (3) true glacial moraines, especially terminal moraines, like the one which extends the full length of Long Island, and marks the southernmost limit of the great ice sheet; and (4) the generally widespread distribution, over most of the glaciated area, of heterogeneous glacial débris, both unstratified and stratified, which is clearly transported material, and which typically rests upon the bed rock by sharp contact (Fig. 214).

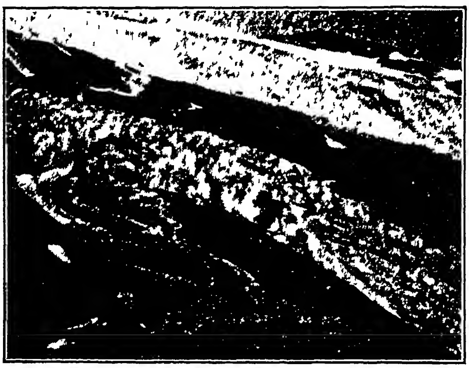

Fig. 192
A side view of Asulkan Glacier near Glacier, British Columbia (Photo by the author)

Extent, Movement, and Depth of the Ice. — An area of about 4,000,000 square miles of northern North America was covered by ice at the time of maximum glaciation. Map Figure 193 shows not only the extent of the ice, but also the three great centers or districts where the glacial ice, compacted from snow, accumulated most abundantly. From each of these three centers — Labradorean, Keewatin, and Cordilleran — the ice slowly spread in all directions until the three great ice sheets coalesced everywhere

except in one relatively small district. This nonglaciated area covers about 10,000 square miles, and lies mostly in southwestern Wisconsin (Fig. 193). It represents a district where the Labradorean and Keewatin Glaciers did not quite join.

The Labradorean and Keewatin Glaciers completely covered the land areas which they invaded. Even the highest mountains

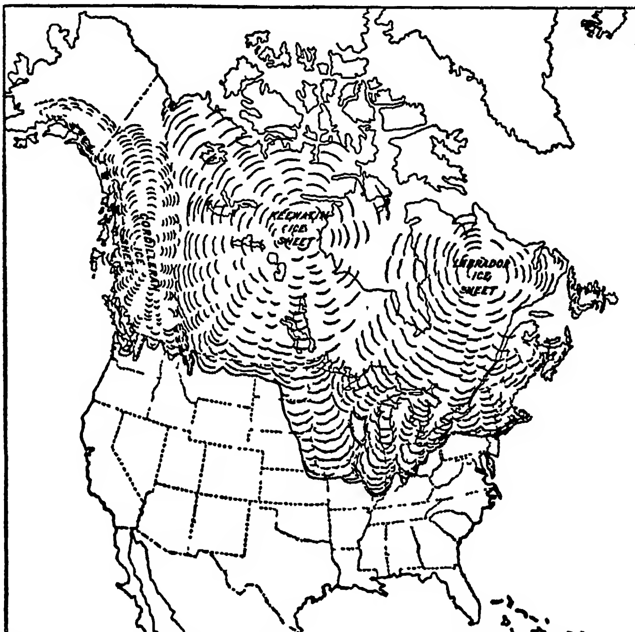

Fig. 193

Map of North America showing the extent of the ice sheets during the Ice Age. (After U S. Geological Survey)

of New England and New York were submerged under the ice flood. The Cordilleran Glacier did not so completely bury the landscape, many of the highest peaks having projected through the ice. The general depth of the vast glaciers was from one to two miles or more.

A great ice sheet also covered about 700,000 square miles of northern Europe during the Ice Age. It radiated from the

Scandinavian region, and spread southwestward over nearly the whole of the British Isles; southward into central Germany; and southeastward into central Russia.

The fact that glacial ice flows as though it were a viscous substance is well known from studies of present-day glaciers in the Alps, Alaska, and Greenland A common assumption either that the land at the center of accumulation must have been thousands

Fig 194

Snow and ice-clad Mt St Elias, Alaska The summit lies about 3 miles above the glacier in the foreground (Photo by Rau Art Studios, Philadelphia.)

of feet higher, or that the ice there must have been immensely thick in order to permit flowage so far out from the center, is not necessary. For instance, if one proceeds to pour viscous tar slowly in one place upon a perfectly smooth, level surface, the substance will gradually flow out in all directions, and at no time will the tar at the center of accumulation be very much thicker than at other places. The movement of the ice from one of the great centers was much like this, only in the case of the glaciers

the accumulation of snow and ice was by no means confined to the immediate centers of accumulation.

Successive Ice Invasions. — It has been established that the front of the great continental glacier underwent many more or less local advances and retreats. In the northern Mississippi Valley there is positive proof of several (perhaps five or six) important advances and retreats of the ice which gave rise to true inter-

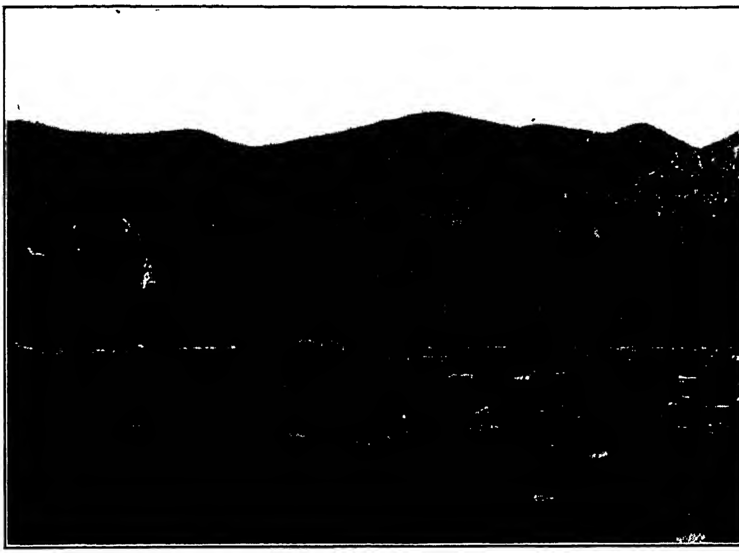

Fig. 195

Detail view of part of the tide-water terminus of Taku Glacier in southern Alaska. Cliff of ice is about 200 feet high (Photo by Rau Art Studios, Philadelphia)

glacial stages. The strongest evidence is the presence of successive layers of glacial débris, a given layer often having been oxidized, eroded, and covered with vegetation before the next (overlying) layer was deposited. In drilling wells through the glacial deposits of Iowa, for example, two distinct deposits or layers of vegetation are often encountered at depths of from 100 to 200 feet. Near Toronto, Canada, plants which actually belong much farther south in a warmer climate have been found between two layers of glacial débris. Thus we know that some,

at least, of the ice retreats produced interglacial stages with warmer climate, and that they were sufficient to reduce greatly the size of the continental ice sheet, or possibly to cause its entire disappearance.

Origin of Glaciers

Perpetual Snow-fields. — Glacial ice is derived from snow. Two conditions are necessary for the formation of glaciers — low temperature and sufficient snowfall. These conditions obtain in perpetual *snow-fields*, that is, areas over which the snow persists season after season, and year after year (Fig 194). In such snow fields there is a tendency for snow to accumulate faster than it can be removed by melting or evaporation, and the excess snow is removed by being transformed into glacial ice as explained below. Some snow fields are too small to produce enough ice for glacier motion.

The line above which snow is always present is called the *snow line.* It is, in other words, the lower edge of a snow field. Snow fields occur in all the regions already mentioned as containing glaciers. They are not uncommon, usually at relatively high altitudes, on all the great land divisions of the earth except Australia, which has none, and Africa, whose few small snow fields are confined to a group of high mountains in the east-central part of the continent.

In the Antarctic, and in parts of the Arctic, regions the snow line is at or near sea level, while in the equatorial region it is from 15,000 to 18,000 feet above sea level. In certain other parts of the world the altitudes of the snow line (in feet) are approximately as follows: Alps, 9000; Pyrenees, 6500; southern Norway, 5000; Himalayas, 15,000 to 17,000; Bolivian Andes, 15,000 to 18,000; southern Chile, 2000; Mexico, 15,000; Sierra Nevada, 11,000 to 13,000; Cascade Mountains, 8000 to 11,000; Colorado, 12,500; Yellowstone Park, 10,500, Glacier Park, Montana, 9000; southern Alaska, 5000; and southern Greenland, 2000.

Change of Snow into Ice. — Every perpetual snow-field is also, in part at least, a field of ice. As the snow of such a field accumulates it gradually undergoes a change, especially in its lower portions, first into granulated snow, called *névé*, and then into solid ice. In the late winter and early spring, snow banks in the northern United States often exhibit such a granular

appearance. In a snow field the névé grades downward into porous ice, and finally into solid ice.

The transformation of snow, through névé to ice is effected mainly by the weight of overlying snow which squeezes together and compacts the snow crystals, and by rain or melting snow working down into the snow there to freeze and fill spaces between the snow crystals. When the ice beneath a snow field becomes deep enough (usually at least several hundred feet), the spreading action or flowage develops, and a glacier is formed. Repeated falls of snow over the gathering ground of the glacier keep up the supply of glacial ice.

Movement of Glaciers

Rate of Movement. — The average rate of movement of glaciers is far less than that of rivers. Many observations have shown that the average rate of movement of the glaciers of the world is not more than a few feet per day. Most of the valley glaciers of the Alps move from one to three feet per day, and this is about an average rate for glaciers of this type. A most exceptional case is a certain glacier, extending as a tongue of the great Greenland ice sheet, whose rate has been found to be 60 to 70 feet per day. Some of the very large glaciers of Alaska move at rates of from 4 to 40 feet per day. A glacier advances across country only when its rate of movement is greater than its rate of melting.

Laws of Glacier Motion. — The nature of glacier motion is by no means simple. It involves *differential motion* in a rather complex sense of that term. Brief mention of most of the so-called "laws of glacier motion" will serve to make clear the complicated nature of the movement. These laws, which apply most typically to valley glaciers, are as follows:

1. A glacier, to a greater or less extent, actually glides or slides over the earth's surface. This is abundantly proved by the eroded, and often polished and striated, rock surfaces left by glaciers.

2. The top portion of a glacier moves faster than the bottom, because of friction of the glacier on its bed. This has been proved by observing the change in position of a vertical line of pegs driven into the steep side of a valley glacier.

3. The middle portion moves faster than the sides because of

friction of the glacier against its containing banks. This is easily proved by observing the changing position of a row of marked objects placed across a valley glacier

4. The velocity increases with steepness of slope of the bed. This has been proved particularly for certain glaciers in the Alps. It must be so because gravity is the ultimate force which causes the motion.

5. The velocity increases with the thickness of ice. This again is due to the fact that the force of gravity is more effective in causing movement if a body of glacial ice on a slope is relatively thick

6. The velocity increases with temperature. In warm weather a glacier moves faster than in cooler weather, that is, it moves faster when it is melting and contains more water

7. Velocity increases with straightness of course. A glacier flows less rapidly through a crooked valley because the friction is greater as the ice current rounds the curves.

8. Velocity diminishes with roughness of bed. The motion of the glacier is retarded by being forced over inequalities or obstacles in its bed.

9. Velocity diminishes with amount of load in the basal portion. This is because of increased friction of the glacier on its bed.

10. The line of greatest velocity is more winding than that of the glacial channel Just as in a river, the tendency also in a winding glacier is for the line of greatest current to swing back and forth from one side to the other.

11. A stream of ice does not conform to minor irregularities of the sides of the channel. A glacier several hundred feet thick may move past the end of a tributary valley without flowing into the latter to seek the general ice-level. In this respect, glacier movement is very different from that of water.

Except for the force of gravity which inaugurates the movement, the cause of glacier motion is not yet definitely known. Several theories have been advanced, but it would carry us into too great detail to discuss them in this book.

Lower Limits of Glaciers

We have already learned that glaciers almost invariably originate in regions of perpetual snow. A rare exception to this

rule might be the formation of a reconstructed glacier below the snow line. Under favorable topographic conditions, most glaciers of considerable size flow down to greater or less distances below the snow line. This is particularly true of valley glaciers. Many small hanging glaciers move little if any below the snow line. Piedmont glaciers generally form well below the level of the snow field. Ice caps often send tongues of ice below the edge of the snow field. Continental glaciers usually lie very largely within snow fields, though around their borders the ice may extend beyond the snow line.

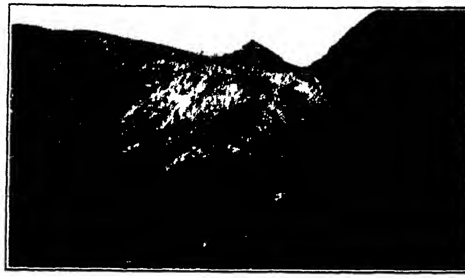

Fig. 196
The Illecillewaet Glacier, British Columbia, as it appeared in 1913. Compare figure 197. (Photo by Miss A. A Heine.)

Valley glaciers not uncommonly move some miles beyond, and several thousand feet below, the line of perpetual snow. A comparison of altitudes of some examples of lower limits of glaciers with the altitudes of the snow line in the same regions as above listed will be instructive in this connection. In the southern Sierra Nevada Range of California the lower limit of glaciers is about 12,500 feet. On Mt. Shasta in northern California it is about 9000 feet. The lower limit in the Cascade Mountains of Washington is about 4500 feet, while at the same latitude in the Rocky Mountains of Montana it is about 6500 feet, the

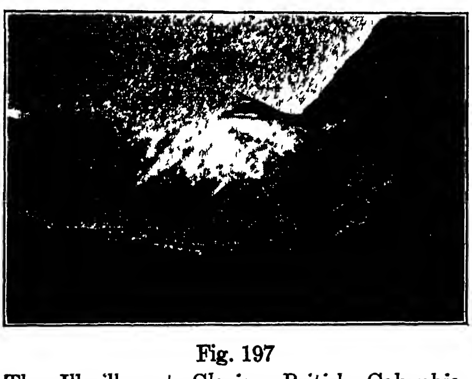

Fig. 197
The Illecillewaet Glacier, British Columbia, as it appeared in 1921. Compare with figure 196, and note the amount of retreat of the ice. (Photo by the author.)

difference being due mainly to the greater snowfall in the former region. In southern Alaska a number of the great glaciers move down to tide water, there to break up in the form of icebergs. Glaciers of southern Greenland reach the sea. In the Alps the lower limit is about 4000 feet. A remarkable case is in New Zealand where large glaciers on South Island flow down into subtropical forests of tree ferns.

Fig 198

A great transverse crevasse in South Sister Glacier, Cascade Mountains, Oregon. (Courtesy of U. S. Forest Service)

The position of the lower end of a glacier depends upon the relation between rate of movement and rate of melting and evaporation of the ice. When rate of movement predominates over rate of evaporation and melting, the end of a glacier advances, and vice versa. A rather delicate balance will cause the end of a glacier to remain stationary for a time A series of seasons of heavy snowfall over the gathering-ground of a glacier will in time cause advance, while a series of seasons of light snowfall will cause retreat. "There are reasons for believing it probable that there are cycles of advance and recession, due, perhaps, to climatic variations; and careful records are now being kept in the hope of discovering the cause for variations in the position of ice fronts" (Tarr and Martin).

Most of the glaciers of Europe and North America are now retreating. Thus the Rhone Glacier in the Alps has retreated a considerable fraction of a mile in the last 30 years. The

Illecillewaet Glacier in the Selkirk Mountains has retreated hundreds of feet during the last 20 years (Figs. 196 and 197). Nisqually Glacier on Mt. Rainier, Washington, was about a fifth of a mile longer in 1885. The tide-water front of the great Muir Glacier of Alaska has retreated several miles in the last 25 years.

Structure of Glaciers

Crevasses. — The surface of a glacier is usually very rough, irregular, and broken, often making travel over it difficult, or even dangerous. The roughness is due in part to irregular melting of the ice; to streams of water which melt and erode channels in

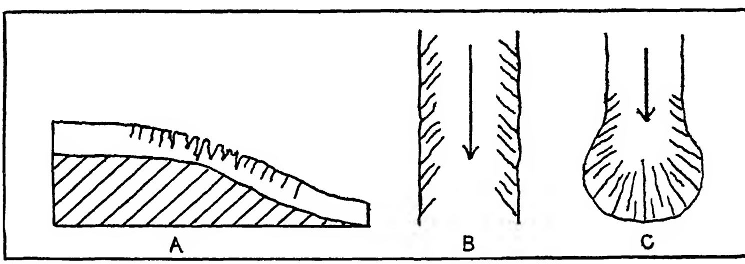

Fig. 199

Sketches showing origin of crevasses in glaciers A, structure section showing transverse fissures, B and C, ground plans showing marginal and longitudinal fissures (Drawn by the author.)

the ice; and to irregular accumulations of rock débris, called moraines, described beyond. The major irregularity and roughness of surface is, however, due to the presence of numerous small and large cracks and fissures which will now be described and explained. They are of three general types. They vary in width up to 20 feet or more, and in depth to hundreds of feet.

Much like molasses candy, ice tends to crack when subjected to a relatively sudden force, particularly a force of tension. Thus where there is a rapid increase in slope across the bed of the glacier, the ice may not be able to mold itself over the salient without rupture, and *transverse crevasses* develop across the glacier (Fig. 198). This is because tension in the upper portion of the glacier is greater than in the lower portion over the salient in the bed

(Fig. 199). A rapid change of slope of only a few degrees is usually sufficient to cause transverse crevasses. Owing to the forward motion of the ice, old crevasses often close up, and new ones develop over the salient.

Due to the greater velocity of the central portion of a valley glacier, stresses and strains set up in the marginal portions often cause *marginal crevasses* to develop. Such cracks usually extend obliquely upstream from each margin of the ice well into the glacier at angles of approximately 45° (Fig. 199).

Where a glacier spreads laterally in a broader portion of a valley, or where it terminates and spreads out on a nearly flat surface, *longitudinal crevasses*, that is, cracks roughly parallel to the direction of ice-flow, usually develop. In such cases the ice by fracturing yields to the force of tension which is caused by relatively rapid spreading (Fig. 199).

Fig 200

A bergschrund at the head of a glacier Swiss Peak, British Columbia. (Photo by L. G. Westgate)

A type of crevasse not really within the body of the glacier should be mentioned. This is the *bergschrund* which develops at the head of the glacier where the glacier motion begins. This fissure (or series of them) forms where the thick body of ice, névé, and more compacted snow of the snow field draws away from the thinner, less compacted snow of the upper margin of the snow field (Fig. 200). The bergschrund will be referred to again in the discussion of glacier erosion.

Layers. — The ice of a glacier is often crudely stratified. This is because the ice of the snow field is built up of successive falls of snow, each of which has certain more or less characteristic features of texture, compactness, depth, etc. When changed into ice, some of the *layers* are more porous and white than others

which are very compact and blue. Also, during considerable intervals between falls of snow, especially between the seasons, more or less dirt often accumulates on the surface of the snow field. Such dirt bands greatly accentuate the stratified appearance of the ice which is, as a rule, best developed toward the upper end of the glacier. It is, however, often more or less noticeable even at the very end of a glacier (Fig. 185) in spite of the complicated motions to which the glacial ice has been subjected.

Veinlike structures are often developed locally where porous ice is subjected to an extra degree of compression during the glacier movement, causing it to become solid (and blue) by squeezing out the air.

A crude stratiform or layered structure also develops, especially in the deeper parts of a glacier, by the sliding or shearing of one part of the ice over another. Such sheared surfaces may at times look something like stratification surfaces.

Moraines

Most glaciers carry, or drag along, more or less rock débris ranging in size from very finely divided material to great boulders. Such débris is transported by a glacier either on its surface, or within it, or in or under its bottom portion. The term *moraine* applies to all material gathered, transported, and deposited by glaciers. Morainic material is represented partly by rock fragments which are rolled or washed down upon the glacier, and partly by rock fragments eroded by the glacier from the bed and sides of its channel. Morainic material carried on top of the glacier may be called *superglacial;* that frozen within it, *englacial;* and that in and just under its bottom portion, *subglacial.*

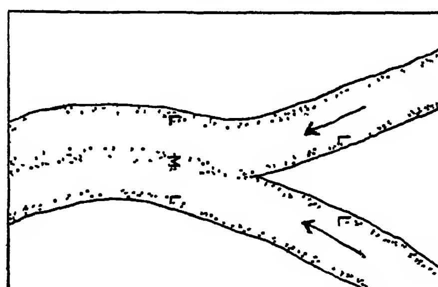

Fig. 201

Ground plan sketch showing the origin of a medial moraine by the coalescence of two lateral moraines. (Drawn by the author.)

The superglacial débris is mostly of two classes — lateral and medial. Where it is arranged along the sides of the glacier it is called a *lateral moraine*. It consists mainly, or wholly, of material which has rolled or washed down upon the margins of the glacier from its bounding rock walls or sides. It is usually most conspicuous toward the end of the glacier where it forms ridges of earth from a few feet to a hundred feet, or more, high. A *medial moraine* is a belt of rock débris on the surface of the glacier, well away from its margin. It may or may not be in the middle of the glacier. It nearly always results when two glaciers flow together, so that two adjacent lateral moraines (one from each glacier) unite to form a medial moraine (Fig. 201). A trunk glacier, formed by the union of several tributaries, may show several medial moraines.

Certain interesting topographic features of the surfaces of glaciers result from the influence of the superglacial moraines. Not only do such moraines often form ridges by their accumulation, but also (when thick enough) they protect the ice immediately underneath them against melting and evaporation, by which processes the general surface of the glacier is very appreciably lowered. In this manner the morainic ridges are accentuated in height. For the same reason, large blocks of rock may be left perched temporarily upon ice pedestals or columns. A very thin surface layer of rock débris absorbs enough heat to cause the ice just underneath it to melt faster than otherwise, and so depressions of various shapes and sizes result.

Englacial material results partly from rock débris which accumulates on the surface in the catchment basin, and is buried under new falls of snow which change to ice, and partly from débris which falls into crevasses in the glacier farther down its course. Englacial material may travel miles through the body of a glacier, and then emerge at or near its terminus. Marked objects thrown into the sources (catchment basins) of glaciers many years ago have been found to emerge at or near the lower ends of the glaciers. When, through melting and evaporation of the top ice, some of the englacial material appears at the surface of the glacier, it becomes *superglacial material*

Subglacial material, also called the ground moraine, is lodged within, or dragged along just under, the bottom of a glacier. It consists of superglacial and englacial materials which make their

way to the bottom, together with materials picked up by glacier erosion. The greatest portion of all morainic material is carried in the bottom portion of a glacier.

All rock débris — superglacial, englacial, and subglacial — carried along by a glacier ultimately tends to reach its terminus

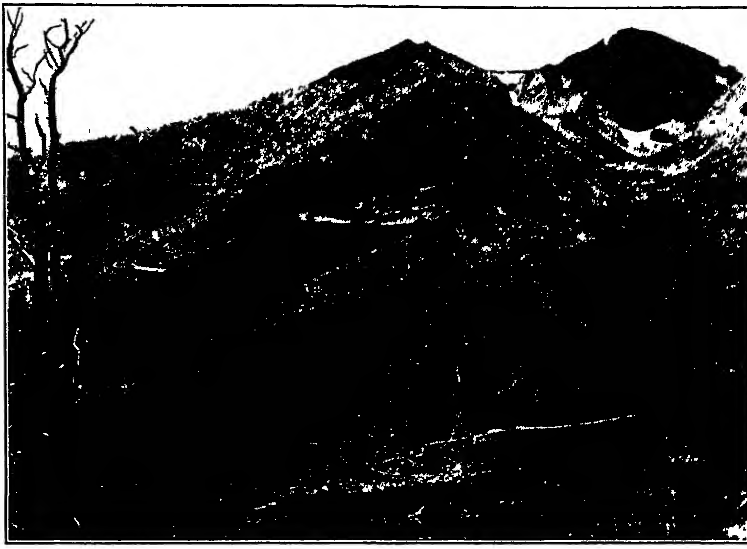

Fig 202

Great morainic loop left by a former glacier at the mouth of the Chasm, Long's Peak, Colorado. (Photo by W. T. Lee, U. S Geological Survey.)

where it accumulates to form the *terminal moraine.* Such a moraine becomes most conspicuous when the terminus of the glacier remains practically stationary for some time (Fig. 202).

Drainage of Glaciers

In mild weather, a glacier nearly always has streams of water upon it. Most of this water results from melting of the ice, but some of it may flow down the valley sides, and thence upon the glacier. Most of these streams are very temporary, and they usually do not flow far before pouring into crevasses, or over the sides or end of the glacier. Some of the water follows englacial

channels for a time, and some of this englacial water may issue from the sides of the glacier above its bottom in the form of springs. The general tendency is, however, for the water to accumulate in the form of a stream at the bottom of the glacier, and to issue at or near the terminus of the latter, often from a tunnel (Fig. 190). The water of such a subglacial stream is characteristically turbid and whitish because it is charged with very finely ground particles of fresh, unweathered rock. Ordinary streams in flood are usually brownish or yellowish because charged with weathered material rich in oxide of iron.

Glacial Erosion

How Glaciers Erode. — Glacial ice, like running water, can accomplish more or less erosion of loose and soft rock materials.

Fig 203

A glaciated ledge of sandstone high up in the Rocky Mountains Glacier Park, Montana (Photo by the author)

But, like water, ice has considerable power to erode relatively hard rock only when it is properly supplied with tools.

An important process of glacial erosion is *corrasion,* that is the rubbing and grinding action of rock fragments either frozen into

the bottom and sides of the glacier, or situated just underneath it. Much of the work of erosion is, then, accomplished not by the ice itself, but rather by the rasping, grinding, and rubbing action of the rock fragments carried along by the glacier. Rock surfaces which have been subjected to glacial corrasion are characteristically smoothed and usually more or less scratched, striated, or grooved (Fig. 203). Such scratches and grooves are known as *glacial striae* A glaciated rock surface of this kind constitutes one of the best proofs of the former presence of a glacier in a region, and the striae indicate the direction of the glacier movement.

Another important process of glacial erosion is *plucking* or *pressure.* This consists in separating from the bed rock, and pushing along, blocks of rock already more or less loosened by joint cracks. Highly jointed rocks are, therefore, most susceptible to glacial plucking. Such joint blocks, as well as any other boulders and pebbles, which are rubbed either against the bed rock, or against each other, by the movement of the glacier, often become faceted and striated.

Fig. 204

A ridge of granite strongly scoured from right to left by a glacier. Tuolumne Meadows, California. (Photo by the author.)

Efficacy of Glacial Erosion. — Considering the present and past condition of the earth, the total work of ice erosion as compared to that of running water is slight, because glacial erosion is, and has been, much more restricted in its action both in space and time. During the last 50 years various opinions have been expressed in regard to the efficacy of glacial erosion. Some geologists have ascribed great erosive power to glaciers, while others have considered them to be weak erosive agents. The present consensus of opinion is that, under reasonably favorable conditions, glaciers accomplish a truly important work of erosion.

Fig 205
A U-shaped glaciated canyon in the Rocky Mountains Swiftcurrent Valley, Glacier Park, Montana (Photo by the author)

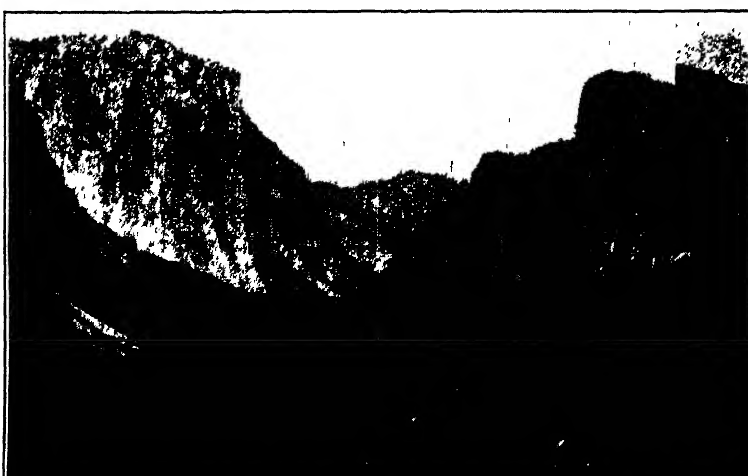

Fig. 206
Looking eastward through the deep, steep-sided Yosemite Valley, California. El Capitan on the left and the Cathedral Rocks on the right. (Photo by D. W. Johnson for the U. S Geological Survey)

Conditions for ice erosion are exceptionally favorable where a thick glacier, shod with numerous fragments of hard rock, moves over relatively soft, or highly jointed, rock because the grinding tools are hard and abundant; the work to be done is easy; and the pressure of the ice on the bed rock is great.

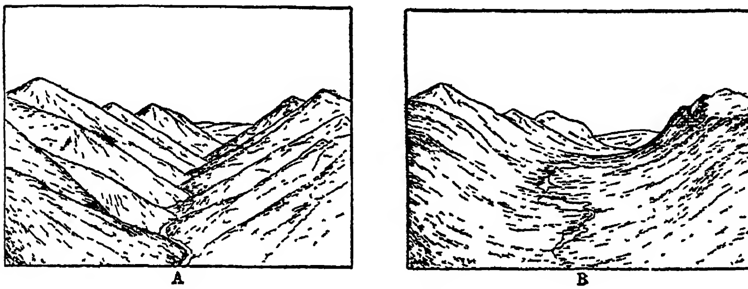

Fig 207

Diagrams showing a stream-cut valley (A) as it appears after glaciation (B). (After U S. Geological Survey)

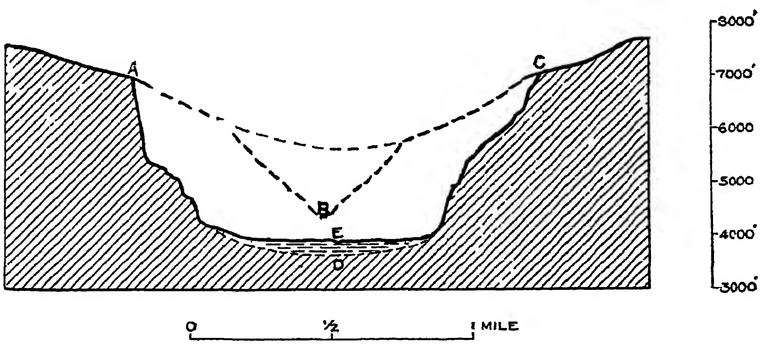

Fig 208

Profile section across Yosemite Valley, California, showing its condition before glaciation (B) and after it. (After Matthes, U S. Geological Survey.)

We have no evidence that large valleys have been developed, or that the general landscape has been profoundly altered, by glacial erosion, but we do have positive evidence that many valleys have been very notably modified, and landscapes have been at least somewhat altered by glacial erosion.

The efficacy of ice erosion over a large territory is particularly well shown by the effects of the passage of the vast Labradorean Glacier over southeastern Canada, northern New England, and northern New York. Common and characteristic features of this territory are the almost total absence of residual soils which must have been very abundant before the advent of the ice, and the large number of rounded, glaciated, bare surfaces of very hard and fresh rocks. The evidence is clear and conclusive that the glaciers

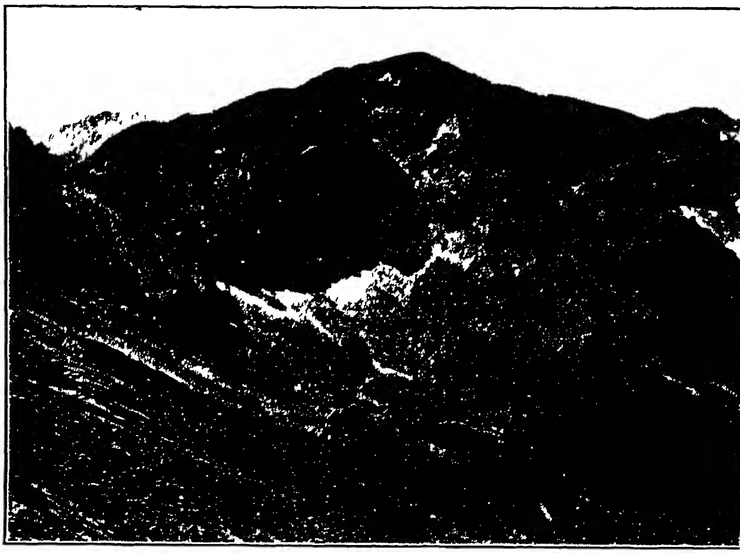

Fig 209

A typical cirque about 3000 feet deep on the west side of Long's Peak, Colorado (Photo by the author)

shod with many fragments of hard rock, eroded not only practically all of the soil and rotten rock from these surfaces, but also at least some of the fresh rock. This is true even at altitudes of one to several thousand feet in many places.

A remarkable example of the power of a valley glacier to erode very hard rock is the famous Yosemite Valley of California. This valley is seven miles long, several thousand feet deep, and broad-bottomed. The rock is wholly a hard granite, but it is unusually highly jointed. Just before the Ice Age, the site of the Yosemite

Valley was a V-shaped canyon about 3000 feet deep. Then a big valley glacier moved through the canyon, filling it to overflowing. The great depth of ice, causing tremendous pressure (and hence effective corrasion) on the bottom and lower sides of the canyon, combined with the unusually highly jointed character of the rock, so greatly facilitated the work of erosion that the V-shaped canyon was deepened hundreds of feet, and its sides were notably cut back and greatly steepened (Fig 208).

Fig. 210

Chasm Lake and the great cirque wall on the east side of Long's Peak, Colorado. (Photo by W. T. Lee, U. S. Geological Survey.)

Characteristics of Glacial Valleys. — A mountain valley through which a thick glacier has flowed relatively recently shows certain unmistakable evidences of the former presence of the ice. Some of the principal characteristics of glacial valleys will now be briefly described.

(1) A valley which has been vigorously glaciated has a broad bottom, and very steep to vertical sides. In other words, it has a U-shaped cross-section or profile instead of the characteristic V-shaped cross-section of a valley vigorously eroded by a stream. This is because a glacier not only erodes the bottom of its valley, but also because it very actively cuts back the sides of the valley, especially toward their bottoms where the ice pressure is greatest. Thus the valley is deepened, its sides are notably cut back and much steepened, and its bottom is

much broadened (Fig. 207). Yosemite Valley (already described) with its great precipitous walls and broad floor is a wonderful example. There are many other examples in the Sierra, Cascade, and Rocky Mountains (Fig. 205), and in Alaska.

(2) Many of the glacial valleys (or canyons) in the mountains just mentioned are much straighter, and more open for long distances, than stream-eroded valleys (or canyons) would be. This is because a glacier has a much stronger tendency to take a straighter course than has a river, and so the lower ends of the ridges (spurs) which project down into the valley alternately from opposite sides are truncated by glacial erosion (Fig. 207).

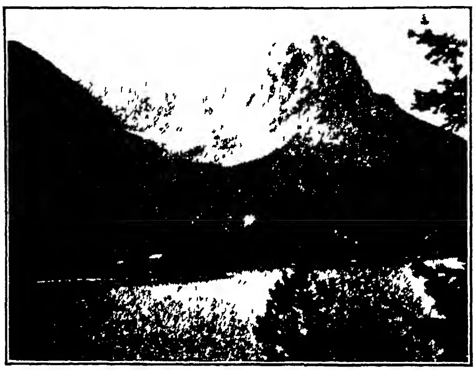

Fig. 211

A hanging cirque opposite Going-to-the-Sun Chalet, Glacier Park, Montana (Photo by the author)

(3) We have already learned that stream-cut tributary valleys very typically join their main-stream valleys *at grade*, that is, at practically the same level. In a glacial valley, however, the tributary valleys show typically a *discordance* of position, that is, they join the main valley much above its bottom and are, therefore, called *hanging valleys*. This is because the lower ends of the tributary valleys are cut back during the process of valley widening by the action of the glacier in the main valley. Even if glaciers occupy the tributary valleys, they are usually too small to cut down their beds as fast as the main glacier. Streams in such tributary hanging valleys usually enter the main-valley streams by waterfalls or cascades. Hanging valleys with waterfalls are grandly exhibited in the Yosemite Valley. Many other examples occur in the Sierra Nevada, Cascade, and Rocky Mountains (Fig. 211), and in southern Alaska, Norway, and the Alps.

(4) A less common feature of glacial valleys is that large glaciers entering the sea may erode their valleys hundreds of feet

below sea level. This is because the moving ice is able to displace the water until its depth becomes so great that the ice is buoyed up and broken off A number of large Alaskan glaciers which enter arms of the sea are now at work deepening their valleys hundreds of feet below tide level. Rivers can cut their channels but very little below sea level.

In this connection mention should be made of certain deep-water, narrow arms of the sea with high steep walls, called *fiords*.

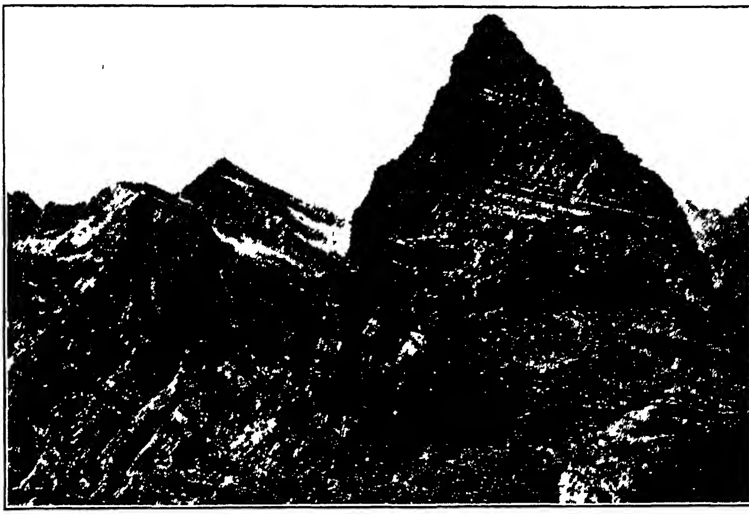

Fig. 212
Matterhorn Peak in Glacier Park, Montana. (Copyright photo by R. E. Marble, Glacier Park, Montana)

They are exhibited on grand scales in Norway and southern Alaska where they are often 10 to 75 miles long, and several thousand feet deep; and on a less grand scale in Maine. All, or nearly all, of them have resulted from erosion of river valleys by glaciers followed by notable subsidence of the land. They are usually too deep to be accounted for by glacial erosion alone. The maximum depth of water in Norwegian fiords is commonly from 1000 to 4000 feet.

Cirques. — The heads of glacial valleys are very commonly characterized by big, steep-sided, amphitheatre-like basins known

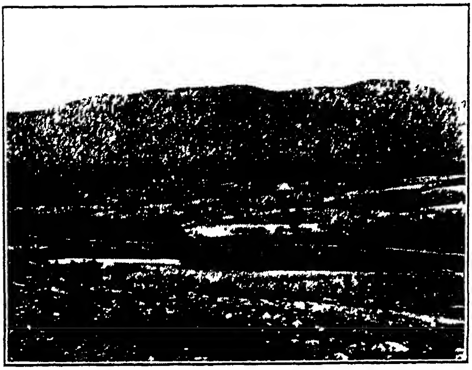

Fig. 213
A valley floor covered with deep glacial drift Near Lyon Mountain, New York. (Photo by the author)

as *cirques*. As we have already mentioned, the main body of snow, névé, and ice of the snow field at the head of a valley glacier tends to pull away from the snow and névé of the upper slopes, leaving a deep crevasse called the *bergschrund* in which the bed rock is more or less exposed. During the warm days of summer, water fills the joint cracks and crevices in the rocks down in the bergschrund, and during the much colder nights this water freezes, forcing apart and loosening some of the joint blocks. Such rock fragments accumulate in the bottom of the bergschrund where, in the later colder season, they are enveloped in ice and in névé formed from new snowfalls. The rock fragments are thus frozen into the head of the glacier and carried along by it. This quarrying or excavating operation, which is repeated season after season, is most effective toward the bottom of the bergschrund, and so the sides of the valley head are cut back and greatly steepened, forming a cirque.

Fig 214
Detail view of a ground moraine left by the great glacier of the Ice Age Adirondack Mountains (Photo by the author)

Cirques, now free from ice or nearly so, are abundant in the Sierra Nevada, Cascade, and Rocky Mountains (Fig. 209), in

Fig 215

Map of the Great Lakes region showing the directions of ice movement and the recessional moraines of the final ice retreat (After Taylor and Leverett, U. S. Geological Survey)

southern Alaska, and in the higher mountains of Europe. They are commonly from one-fourth of a mile to a mile or more wide, with steep to precipitous walls from 500 to 3000 feet high (Fig. 210). Occasionally cirques occupy the positions of hanging valleys, excellent examples occurring in Glacier National Park, Montana (Fig. 211). Cirques constitute striking features of the

landscape in these and other recently glaciated mountains. They often contain small lakes.

Two cirque walls may be cut back toward each other from opposite sides of a mountain mass until only a very sharp divide, known as a *knife-edge* ridge, is left between the cirques. A knife-edge ridge may also develop where glaciers in two parallel valleys erode and steepen the valley sides until only a very sharp divide

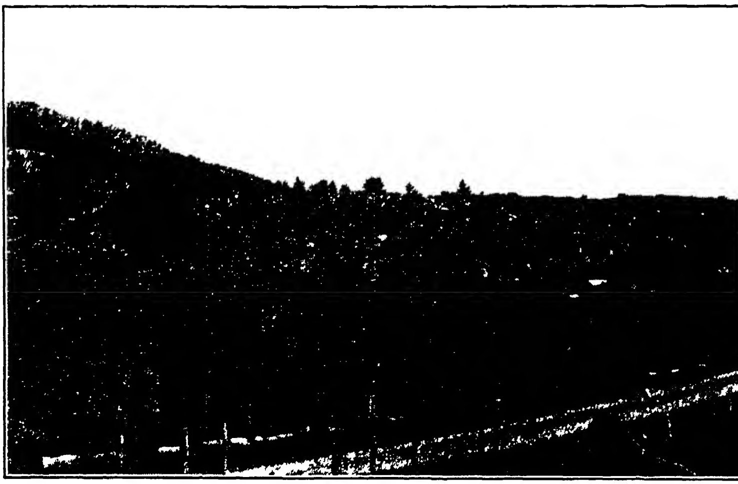

Fig. 216
Part of a boulder moraine Near Baker's Mills, New York
(Photo by the author.)

separates the valleys. If three or more heads of glaciers cut cirques into a mountain mass from several sides at once, a high, pyramid-shaped rock mass, commonly called a *matterhorn,* may result. The type example is the famous Matterhorn of the Alps. Matterhorns are common in Glacier Park, Montana (Fig. 212).

Glacial Deposits

The Drift. — We have already learned that glaciers transport large quantities of rock débris either on their surfaces, or within them, or dragged along at their bottoms. It is heterogeneous material ranging from the finest clay, through sand and gravel,

to boulders weighing many tons. Some of these materials may be deposited during the slow advance of a glacier, but such materials are again very largely eroded and carried along by the advancing ice. Most of the deposits, not again disturbed by the ice, are laid down during the retreat of a glacier, and these are of chief interest to us because they are the ones which are so widespread as a direct result of the recent great Ice Age. Most of the deposits left by the glaciers of the Ice Age are remarkably intact except for relatively little postglacial weathering and erosion.

Fig 217
Parallel morainic ridges Goldsmith, New York. (Photo by the author)

The general term applied to all deposits of glacial origin is *drift*, this name having been given when, before the discovery of the fact of the Ice Age, such deposits were regarded as having been carried (or drifted) over the country by floods and icebergs. Much of Canada and most of the northern United States as far south as New York City, Pittsburgh, St. Louis, and Pierre, South Dakota, are covered by drift from a few inches to several hundred feet thick. It is not shown mainly where bed rock is exposed; where lake and river waters are present; or where there are post-glacial river and lake deposits. The drift bears unmistakable evidences of its glacial origin.

Fig. 218
Side view of a drumlin. Near Elbridge, New York (Photo by the author.)

Some of its material has been transported hundreds of miles, as proved by tracing certain types of rocks in the drift to their parent ledges. An important characteristic of the drift is that it rests upon the bed rock by sharp contact, and usually contains at least some material different from the bed rock, showing that it is transported, and not residual, material

There are in general two classes of glacial deposits, namely, the unstratified *ice-laid deposits* which are left by the ice unaided by the action of water, and the stratified *fluvio-glacial deposits* which are carried and deposited by waters in, or emerging from, glaciers. These two classes will now be briefly described.

Ice-laid Deposits. — *Ground moraines.* These consist of heterogeneous, unstratified rock débris deposited underneath a glacier, especially during its melting and retreat. When it is

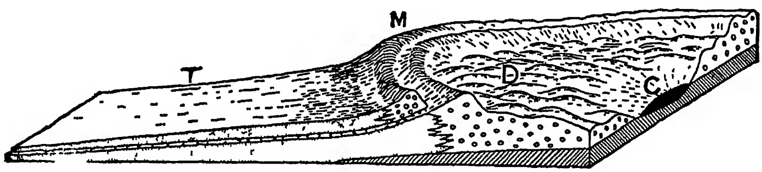

Fig. 219
Sketch showing a terminal moraine, M; an outwash plain, T; drumlins, D; and a kettle hole, C. (After A. Penck)

mostly very fine material with pebbles or boulders scattered through its mass, it is called *till* or *boulder clay* (Fig. 214). The pebbles and boulders are often characteristically faceted and striated as a result of having been rubbed and ground against the bed rock. Ground morainic material is exceedingly widespread in the great glaciated region of North America

Terminal Moraines. Whenever the terminus of a glacier remains in a relatively stationary position for a considerable time much rock débris carried by the glacier accumulates around its end, forming a *terminal moraine* (Fig. 219). Such a moraine, especially as left by the great ice sheets of the Ice Age, is a more or less distinct range of low hills, with depressions between the hills, consisting of very heterogeneous, generally unstratified débris, though at times waters emerging from the glacier may have caused some local stratification. Valley glaciers often leave

looplike terminal morainic ridges across valleys or at their mouths (Fig. 202). A great terminal moraine is more or less clearly traceable across the United States where it marks the southernmost limit of the vast glaciers of the Ice Age. On Long Island it is wonderfully well shown by the ridge of irregular hills extending the whole length of the island.

If, after a glacier has retreated a considerable distance, its terminus again remains relatively stationary for some time,

Fig. 220

A delicately balanced glacial boulder (so-called "rocking stone") 1500 feet above sea level. Near Westhampton, Massachusetts. (Photo by the author.)

another terminal moraine will accumulate around it. Such a so-called *recessional moraine* develops during every considerable pause in the recession of a glacier. Recessional moraines, forming a great succession of curving ridges, are wonderfully displayed to the south of Lakes Michigan and Erie (Fig. 215). These mark successive pauses of the waning Labradorean ice sheet of the Ice Age.

Drumlins. These are unstratified glacial deposits of unusual

interest. They represent, in reality, only a special form of ground morainic material (Fig 219). They are typically low, rounded mounds or hills of till with elliptical bases, long axes parallel to the direction of the glacier movement; and steepest slopes facing the direction from which the ice flowed. They are commonly from 50 to 200 feet high, and one-fourth to one-half of a mile long One of the grandest displays of drumlins in the world is in the general region between Syracuse and Rochester, New York, where thousands of them rise conspicuously above the level of the Ontario Plain (Fig. 218). Drumlins are abundant in eastern Wisconsin, and in a part of Ireland. Some also occur in the Connecticut Valley of Massachusetts, and around Boston.

Fig. 221
A remarkably balanced glacial boulder on top of a mountain 2600 feet above sea level About five miles west of Garnet, New York (Photo by the author)

The mode of origin of drumlins has not been precisely determined, but it is known that they form near the margins of broad lobes of glacial ice probably either by ice erosion and rounding-off of till, or by accumulation of till beneath the ice under peculiarly favorable conditions, as perhaps in longitudinal crevasses.

Erratics. These are glacial boulders left strewn irregularly over the country during the melting of the ice. They vary in size from pebbles to masses as big as small houses. Most of them consist of hard rock, because the softer materials are generally ground up soon by the action of the glacier. Some erratics have been moved but short distances from their parent ledges; many have been transported at least a few miles; while some have been

carried hundreds of miles. Thus boulders of Adirondack Mountain rocks occur in southern New York, and certain erratics in southern Minnesota came from ledges well up in Canada. Erratics are extremely abundant in New England and New York where much land had to be cleared of them before it could be cultivated. They occur even high up on the mountains. The writer has observed erratics of sandstone, derived from ledges in the St. Lawrence Valley a few hundred feet above sea level, on the tops of mountains 4000 feet high. Erratics weighing from 5 to 20 tons have sometimes been left in such remarkably balanced positions on bed rock that they can be made to swing back and forth slightly by pressure of the hand (Fig. 220). Such boulders are sometimes called "rocking stones." The writer recently observed a large erratic standing on edge at the very summit of a peak 2600 feet above sea level in northern New York (Fig. 221). Still another case observed by the writer was a rounded erratic about 14 feet in diameter remarkably balanced on top of another rounded erratic of about the same size (Fig. 222).

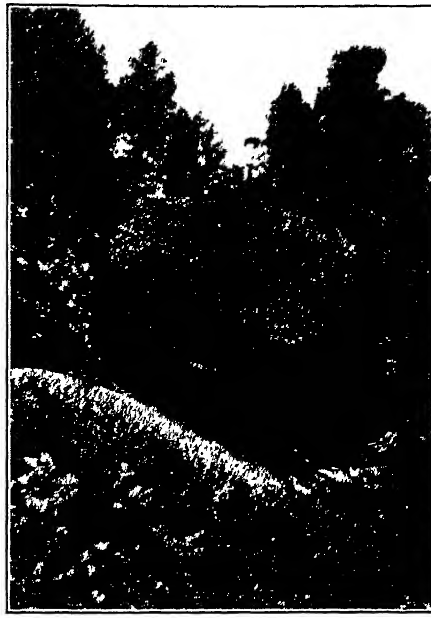

Fig 222

A big glacial boulder remarkably perched upon another boulder. East of Blue Ridge P. O., New York (Photo by the author)

Fluvio-glacial Deposits. — *Valley trains.* Waters emerging from the ice are usually heavily loaded with rock débris. When such waters flow down a valley which slopes gently downward away from the end of a glacier, the tendency is to deposit some or most of the load on the valley floor, often for miles beyond the ice

front, forming a valley train (Fig. 223). Deposits of this kind, somewhat cut away by postglacial erosion, are finely exhibited in most of the gently southward sloping valleys of southwestern New York. Valley trains are of course stratified.

Outwash Plains. When the front of a great glacier pauses for a considerable time upon a rather flat surface, the débris-laden waters emerging from the ice spread in a network of streams and

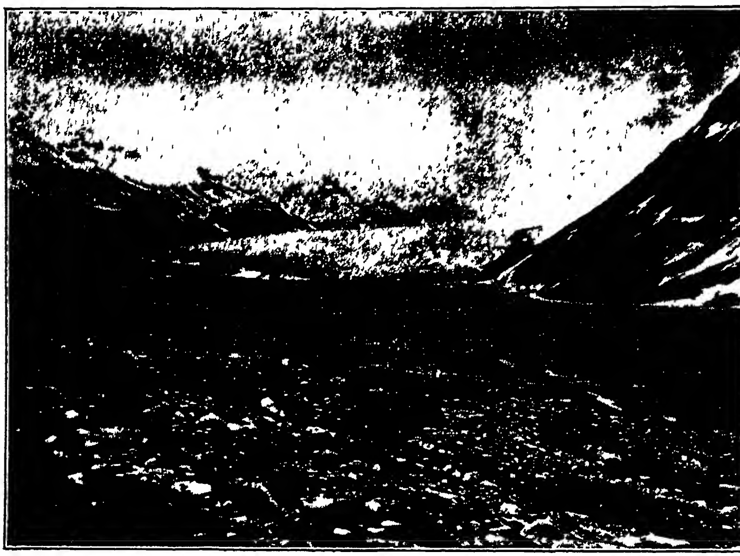

Fig. 223

A broad valley train being formed by a braided stream emerging from a glacier. Hidden Glacier, Alaska. (After Gilbert, U S Geological Survey.)

deposit the débris more or less uniformly over the surface, forming an *outwash plain* (sometimes called a *frontal apron*) (Fig. 219). A very fine illustration is most of the southern half of Long Island lying just south of the great terminal moraine. Outwash plains are of course stratified. They are seldom formed by ordinary valley glaciers.

Depressions from 10 to 100 feet deep, with no outlets and with steep sides, are often formed in outwash plains. These so-called *kettle holes* result from melting of blocks of ice which become

separated from the glacier during its retreat and buried under the outwash material (Fig 219). Kettle holes may also develop in glacial lake deposits where icebergs become stranded, buried under sediment, and subsequently melted. Some of the depressions in terminal and recessional moraines, and also in groups of kames, are kettle holes.

Fig. 224
Kame hills, five miles west of Gloversville, New York (Photo by the author.)

Kames. These are hills of stratified glacial débris with rounded outlines commonly from 50 to 150 feet high. They may exist as isolated hills or in small groups (Fig. 224), or they may be associated with unstratified deposits of moraines. When they are grouped, deep depressions occur between the hills, giving rise to what is called "knob and kettle" topography. They occur most generally in valley bottoms, but sometimes on hillsides, or even on hilltops. They are rather common and widely distributed over the great glaciated region of the northern United States, particularly in association with terminal and recessional moraines. Sometimes they form so-called "kame-moraine" ridges. Kames form at the margins of glaciers by débris-laden streams which heap up the material (usually sand and gravel) as they emerge from the ice. Sometimes the

Fig. 225
Detail view showing the structure of a kame deposit. Gloversville, New York. (Photo by the author.)

débris-charged water rises as great fountains. Kames are now actually in process of construction alongside some of the great Alaskan glaciers.

Eskers. These are long, usually winding, low ridges of strati-~~fied~~ glacial material, mainly consisting of sand and gravel. They are seldom over 75 to 100 feet high, and their crests are generally narrow and rather even (Fig. 226). They are usually less than a mile long, but in Scandinavia and elsewhere individual eskers have been traced many miles. They often look like artificial railway embankments. They were formed by deposition in streams, choked (or overloaded) with glacial débris, either in channels on glaciers, or in tunnels beneath the ice.

Glacial Effects upon Relief, Soils, and Drainage

Effects upon Relief. — We have already shown how valley glaciers have brought about considerable topographic changes by straightening, deepening, widening, and steepening the sides of their valleys, and also how they have developed cirque basins and "knife edge" ridges. We have also stated that the erosion by the great ice sheets of the Ice Age did not profoundly alter the relief of the country over which they moved. Although many hills and low mountains were somewhat scoured and rounded off, and many valleys, especially those of softer rocks approximately parallel to the direction of ice movement, were appreciably deepened and widened, nevertheless the major relief features were left practically unaffected by ice erosion during the passage of the great ice sheets. We may also say that deposition of rock débris by the great glaciers left the major relief features practically unaffected. There was, however, a very appreciable tendency for glacial deposits to accumulate in the valleys during retreat of the ice, but such deposits are only minor details of the larger valleys such as the Connecticut Valley of New England, and the Hudson, Mohawk, Champlain, and St. Lawrence Valleys of New York. Viewed very broadly, the vast glaciers (mainly due to deposition in the preglacial depressions) left the country somewhat less rugged than it was just before the Ice Age.

Effects upon Soils. — It is not too much to say that the passage of the great ice sheets wrought a revolutionary change in the soils of the vast glaciated area of fully 4,000,000 square miles.

Residual soils very largely covered the country before the Ice Age. The movement of the ice caused such soils to be removed from their places of origin, mixed up, and transported, often for long distances. Over eastern and central Canada, where the two greatest accumulations of ice occurred (Fig. 193), ice erosion predominated over deposition, while farther south and southwest glacial deposition predominated. This explains why eastern Canada (except its southern portion) is generally characterized

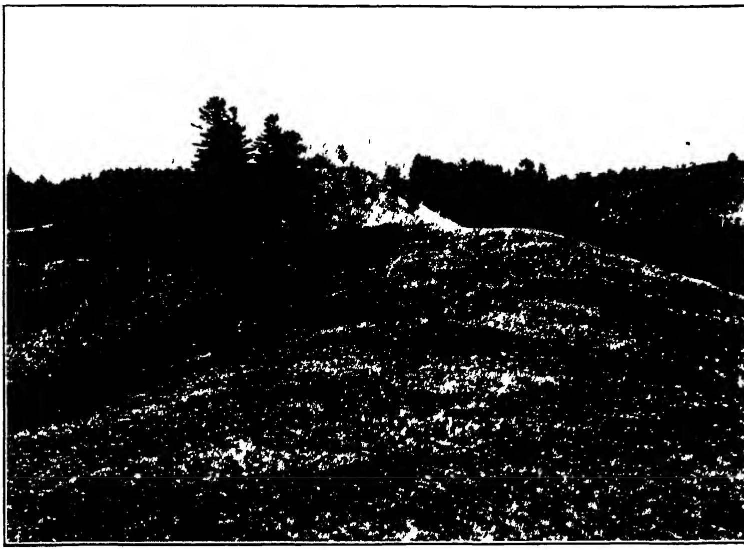

Fig 226

Part of an esker, showing its winding course. North Creek, New York. (Photo by the author)

by bare rock ledges or only thin soils, while deep glacial soils generally prevail over New England, the Upper Mississippi Valley, and the southern parts of Manitoba, Saskatchewan, and Alberta in Canada.

Over extensive areas, such as the upper Mississippi Valley, the soils were made deeper and richer on the average because the glacial-drift soils are there rather uniformly deep, and consist of finely ground rocks of many kinds still rich in the soluble mineral foods for plants. The preglacial soils were not only thinner on

numerous hillsides, but also largely depleted of the rich soluble mineral foods for plants.

In New England and considerable parts of New York and southeastern Canada, the glacial soils are not only too sandy and gravelly to be very fertile, but also usually difficult to cultivate because of the numerous glacial boulders which they contain. These features of the soils are due to the fact that the ice passed over great areas of very hard, crystalline, igneous and metamorphic rocks which, when eroded, produced large quantities of sand, gravel, and boulders.

Effects upon Drainage. — Changes of stream courses, directly resulting from the presence of the great ice sheets of the Ice Age, were numerous in many parts of the glaciated area. Some of these changes were truly far-reaching. Many preglacial valleys were more or less completely filled with glacial débris, causing new streams, which came into existence after the ice melted, to follow courses very different from those of their predecessors of preglacial days. In other cases streams were crowded out of their valleys by the ice itself, and forced to erode new channels elsewhere. Many such new channels have been held to since the disappearance of the ice. Only a very few examples will be mentioned. Immediately prior to the Ice Age, the combined Allegheny and Monongahela Rivers flowed northward into the Erie Basin instead of through the Ohio Valley as at present. Ice occupancy and accumulation of much glacial débris across northwestern Pennsylvania caused the change. Rock River in northern Illinois flowed southward into the Illinois River instead of southwestward into the Mississippi as at present. The preglacial Ohio River followed a devious course for fully 40 miles between Cincinnati and Lawrenceburg instead of the present short-cut between the two places, the change being due to local blockading of the old valley. The Sacandaga River of northern New York formerly flowed southward into the Mohawk River instead of turning eastward into the Hudson River as at present, blockading of its old valley by drift having been the cause of the change. We have already shown (p. 194) how the Missouri River was forced, by the crowding action of an ice sheet of the Ice Age, many miles westward to its present position in South Dakota.

In many cases, where streams were forced to find new channels, they have carved out picturesque gorges, usually containing

waterfalls. A few examples are Niagara Gorge and Falls, and Ausable Chasm, Trenton Falls, and Watkins Glen in New York.

Most of the lakes by far, of the scores of thousands in northern North America, are direct results of the glaciation of the Ice Age. Even the Great Lakes were not in existence before the Ice Age. Some of these numerous lakes occupy rock basins which were scoured out by glacial erosion, but most of them fill basins which were formed by drift deposits blockading valleys, causing the streams in them to be locally ponded. Lakes of these kinds, as well as others, are considered at some length in Chapter XIII.

Non-glacial Ice

Ice in Soils and Rocks. — Over wide areas of the higher latitude regions of the earth, water in the soil freezes during at least part of the time each year, often to a depth of from 1 to 10 feet or more. On freezing, the water in soil expands, causing movements which are of geological importance. The upward movement thus caused explains why curbstones, posts, roadbeds, etc., are often upheaved, and why boulders in the soil tend to work up to the surface. This process also causes a slow *creep* of soils and rock fragments down slopes because the expansive force of freezing lifts the rock particles or fragments at right angles to the slope, and on thawing they tend to settle vertically. By repetition of this process much loose rock material gradually creeps downhill. On steep slopes in high mountains this expansive movement due to freezing of water in the soil or talus piles may initiate landslides. It should also be mentioned that erosion is greatly checked when the soil is frozen.

Ice in Streams. — Along the shores and bottoms of many streams in cold climates ice often envelops rock fragments of various sizes. When the "break-up" comes in the spring, cakes of ice carrying such débris may float long distances before depositing their loads. The shores of the St. Lawrence show many boulders which have thus been transported.

Ice in Lakes. — So-called *ice ramparts* are low ridges or walls of rock débris bordering lakes and ponds, which have been formed by the crowding action of the expanding pond or lake ice upon the shores. If the pond or lake is covered by thick ice at a temperature far below freezing, and then the temperature rises rapidly,

expansion of the ice cover takes place, and loose materials in the shallow water near the shores are crowded upon the latter. This process, many times repeated, often builds up conspicuous ice ramparts.

Sea-coast Ice. — In the Arctic and Antarctic regions, shallow sea-water is often frozen to a depth of a number of feet for some distance out from the shore, during the cold season Along the shore, rocks are frozen into the bottom of the ice, and some débris accumulates on top of it from the shore. When milder weather sets in, such ice " breaks up " into what is called *floe-ice*. Floe-ice not only drifts away and transports much rock material, but parts of it are driven by winds and tides back and forth against the shore, eroding and grinding the rocks.

Icebergs. — Icebergs are formed in high latitude regions where glaciers flow down into the sea, or arms of the sea, and break into fragments, both small and large, which float away Some icebergs rise from 100 to 200 feet or more above the water; extend 1000 feet or more below the surface of the water; and cover many acres, or, in the Antarctic, even several square miles. Since they are derived from glaciers, icebergs carry more or less rock material within and upon them, and this is strewn over the sea bottom, often many hundreds of miles away, as the icebergs melt.

CHAPTER IX

GEOLOGICAL ACTION OF WIND

Importance of Wind Work

Wind is an important geological agent of erosion and transportation of rock material, but is not as effective as running water. Most people by far live in humid regions where the surface of the earth is largely protected by vegetation, and so there is a general lack of appreciation of the really great work accomplished by wind. But even in humid regions, wind action is by no means slight. Every one has witnessed large clouds of dust stirred up from freshly cultivated fields during periods of dry weather in late spring. Dust of this kind is often blown for miles. By such removal of soil, young crops are often injured or ruined, and the blown soil may bury other vegetation near by. The action of wind is strikingly exhibited in humid regions along and near shores of the sea and of large lakes where sands are picked up and transported in large quantities, often to accumulate in the form of dunes.

It is in arid and semi-arid regions, however, that the wind is most effective as a geological agent. The importance of wind work becomes impressive when we realize that desert conditions prevail over about one-fifth of all the lands of the earth. In deserts weathering effects requiring moisture in the air are reduced to a minimum; stream action is in general much less important as a factor of erosion and deposition than in humid regions; and frost action, due to lack of water, is relatively unimportant. Temperature changes in deserts are, however, exceptionally great and rapid, as between night and day, and so the rocks, which are nearly everywhere directly exposed because free from vegetation, are broken up relatively fast as a result of repeated and rapid expansion and contraction (see page 61).

Winds not only erode, transport, and deposit rock materials, but they also stir up waves and shore currents which in turn

become effective and important geologic agents, as discussed in Chapter X.

Transportation by Wind

It is as an agent of transportation that wind accomplishes its greatest work. Corrasion by wind action cannot proceed without transportation of loosened materials, but tremendous quantities of rock materials, already loosened and sub-divided by processes other than corrasion by the wind, are transported by the latter.

What are some of the sources of the finely divided rock material which is transported by winds? Most of the material by far is picked up from dry surfaces of loose, fine materials of all kinds in all sorts of regions, but especially in deserts where such materials are blown about by every wind. Some of it is directly derived from rock ledges by the erosive action of the wind itself, as explained beyond. Considerable quantities of dust are contributed to the atmosphere by explosive eruptions of volcanoes whereby lava is pulverized and shot far into the air (Fig. 277). During the explosions of Krakatoa (p. 323), a tremendous quantity of finely divided and pulverized rock was forced miles into the air, and some of it was carried completely around the earth and remained suspended for many days, causing the famous red sunsets of 1883. Several cubic miles of volcanic dust were forced out of Katmai Volcano, Alaska, in 1912 when the mountain exploded. This dust caused darkness for many miles around for more than two days; and at a distance of 100 miles it accumulated to a depth of 10 inches.

The almost inconceivable transporting power of strong winds over deserts is illustrated by the well-known "sand storms" of the Sahara Desert. In such a great storm many cubic miles of dust and sand-laden air sweep miles across the country. It has been estimated that one cubic mile of air in such a storm carries at least 100,000 tons of rock material. Dust from the Sahara is known to be carried hundreds of miles out into the Atlantic Ocean. According to an estimate, a great storm in 1901 carried nearly 2,000,000 tons of finely divided rock material from northern Africa into Europe. In two days some of the dust fell in Italy and in three days some of it reached central Germany.

Wind Erosion

Wind picks up and carries along great quantities of dry, loose, finely divided material, but of itself it has little or no power to erode solid rocks. Wind, like water, effectively erodes rocks when properly supplied with tools, that is, when it has rock fragments with which to work. When fine material, especially grains of

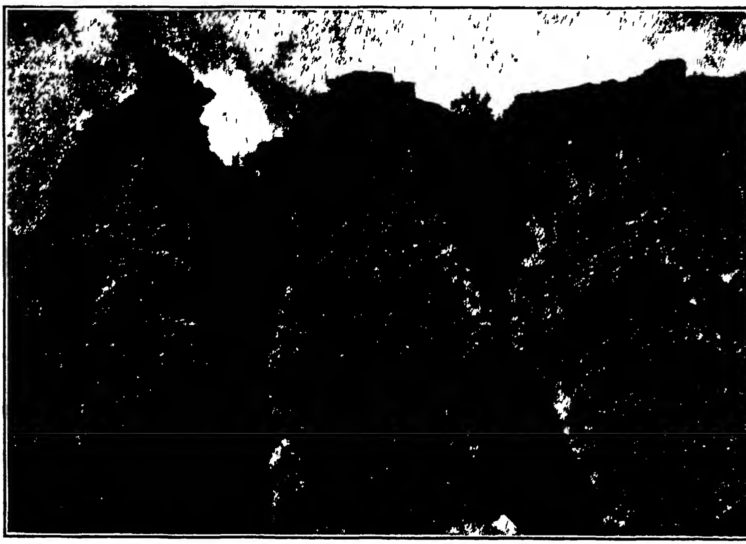

Fig. 227

Wind and rain sculptured, soft, limy sandstone. Los Frigoles Canyon, New Mexico (Photo by Harnden, West Roxbury, Massachusetts.)

sand, are driven by wind with high velocity against barren rocks, the latter are worn (corraded) and often polished by the process. The principle involved is that of the sand blast used in cleaning and polishing decorative and building stones, and in etching glass. Where rock ledges show many local variations in composition and hardness, they are often etched by wind erosion into very irregular, and often fantastic, forms (Fig. 227).

A surprising amount of erosion may be accomplished by the wind, under very favorable conditions, in a short time. A plate

glass window in a Cape Cod lighthouse is said to have been worn to opaqueness during a single hard wind storm. Window glass directly exposed to hard winds on Cape Cod is known to have been completely worn through within a few weeks or months.

Wind-driven sand has its greatest erosive power relatively close to the ground because the heavier and larger fragments, not being lifted so high, there accomplish the greatest work. Telegraph poles in desert regions often must be especially protected else they will be cut down by sand driven against their bases. Pebbles and boulders on deserts sometimes have more or less angular faces carved upon them by wind erosion, and rock platforms are often kept worn smooth and hard. The finer products of rock weathering are often removed about as fast as they form. Larger rock fragments on the surface are gradually worn smaller. In the arid and semi-arid southwestern states of the United States, cliffs are often undercut by the abrasive (or corrasive) action of the wind, sometimes with the development of large caverns The famous Sphinx, and even the pyramids, of Egypt have been very considerably roughened by the corrasive action of wind.

Fig 228

Wind and rain sculptured cross-bedded sandstone. Tensleep, Wyoming (Photo by Darton, U. S. Geological Survey)

Wind Deposition

Dunes. — Hills of wind-blown sand are called *dunes*. They are formed in much the same manner as snow drifts. They are abundant in many regions, as for example along the middle Atlantic Coast of the United States; around the southern end of Lake Michigan in Dune Park, Indiana; and in the desert portions of the western United States. Dunes mostly form in deserts; on and near sandy shores of lakes or oceans where the wind blows toward

the land; and on and near river flood plains, especially in arid regions where the volume of water varies greatly. Dunes seldom attain heights greater than a few hundred feet, though some in the Sahara Desert are said to be more than 1000 feet high.

Fig 229
A crescentic sand dune in Wyoming (Photo by E E Smith, U. S. Geological Survey.)

A dune may begin to build up where there is a slight irregularity of surface, or some obstacle such as a boulder, causing a local check in the velocity of the wind with resultant deposition of some of the load it carries. Once the pile has started, its growth is accelerated by its own shape and size. Where the direction of the wind remains fairly constant, the tendency is for a gentle slope to develop on the windward side, and a steep slope on the lee side. Sand blown up to the crest of the windward side is caught in a relative calm with a back-eddy on the lee side of the hill, and there deposited. The lee side is steeper because the sand rolls down its slope (Fig. 230). Smaller dunes are often somewhat crescent-shaped, caused by the wind driving sand both over and around the dune (Fig. 229). When the winds are rather variable in direction the sand dunes are more irregular in shape.

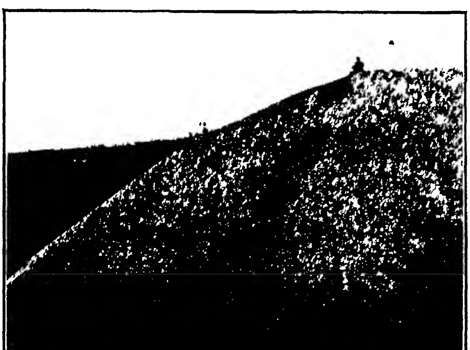

Fig. 230
Top of the great sand dune near Port Burwell, Ontario. (Photo by the author.)

Dune sand is usually crudely stratified, with prominent cross-bedding, due to the varying velocity of the wind which causes

alternately larger and smaller sand particles to be driven up the slopes and deposited in layers. Sand dunes are often beautifully ripple-marked on their surfaces by more or less parallel ridges an inch or more high (Fig. 231).

Migration of Dunes. — Unless prevented by vegetation, dunes usually migrate in the direction of the prevailing wind. The migration is caused by the blowing of the sand up the windward slope, and its deposition on the steeper leeward slope. On a dry,

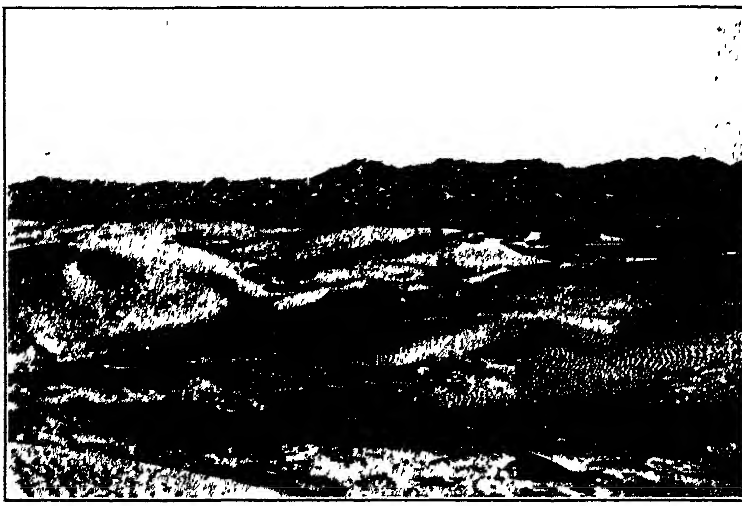

Fig 231

A group of ripple-marked sand dunes in the Imperial Valley, California. (Photo by Mendenhall, U. S. Geological Survey)

windy day the sand can be seen blowing over the crest of a dune. The rate of migration is of course determined by several factors. Most dunes migrate at rates of from a few feet to more than 100 feet per year. A case of unusually rapid movement was that at Kunzen on the Baltic Coast where a large dune encroached upon, buried, and then uncovered a church, migrating about eight miles between the years 1809 and 1869. A pine forest, covering hundreds of acres on the coast of Prussia, was destroyed by migration of dunes between 1804 and 1827. In many places portions of farms have been ruined by migration of dunes within the lifetime of single owners. Forest trees have, in many places, been buried,

killed, and then uncovered by drifting sand (Fig. 233). Such phenomena are well exhibited in Dune Park, Indiana.

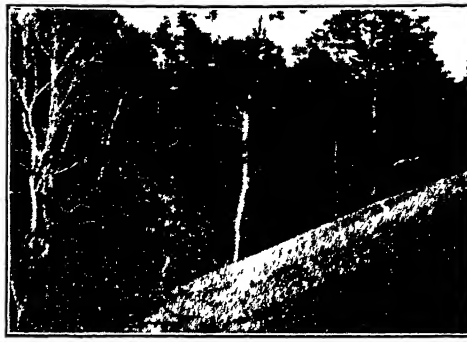

Fig 232

A sand dune advancing upon a forest Near Port Burwell, Ontario. (Photo by the author.)

A region of special interest, which has been carefully studied by Reclus, is the shore of the Bay of Biscay northward from Bayonne. "The sea here throws every year upon the beach, along a line 100 miles in length, some 5,000,000 cubic yards of sand. The prevailing westerly winds, continually picking up the surface particles from the seaward side, whirl them over to the inland or leeward slope, where they are again deposited, and the entire ridge by this means alone moves gradually inland. In the course of years there have thus been formed a complex series of dunes, all approximately parallel with the coast and with one another, and of all altitudes up to 250 feet. These are still marching steadily inward, though at the rate of but three to six feet annually, and whole villages have more than once been torn down to prevent burial, and rebuilt at a distance, to be again removed, within 200 years" (G. P. Merrill)

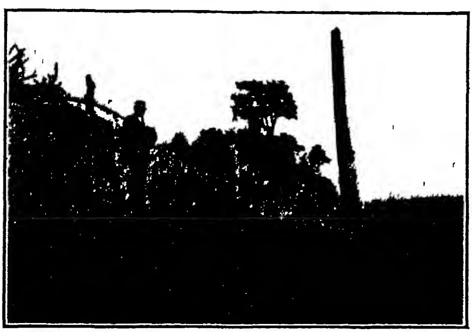

Fig. 233

Tree trunks being uncovered by a migrating sand dune. Near Port Burwell, Ontario. (Photo by the author)

Removal and Deposition over General Areas. — Wind-blown material does not, by any means, always accumulate in the form

of dunes and ridges. Wind action often tends to level off large areas by removing loose materials from higher lands and depositing them in intervening depressions, or piling them against bases of mountains. This is true on a grand scale in portions of the Sahara Desert where certain wide areas of bed rock are kept free from sand by wind erosion, and the sand is piled against the mountain bases, and even up the slopes to heights of 1000 to 2000 feet. In the Great Basin region of the western United States somewhat similar phenomena are not uncommon.

Fig 234
Roots of trees being uncovered by migrating sand Near Port Burwell, Ontario (Photo by the author)

Part of the surface of the Isthmus of Suez has been cut down, by removal of sand, about eight feet, at the rate of four inches per century, the material removed from the higher and drier areas having been deposited in the depressions, often converting marshes into dry land.

According to Dwight, the protective effect of grass was once so destroyed by pasturage on a part of Cape Cod that the wind from the Atlantic Ocean removed sand to a depth of 10 feet from an area of about 1500 acres.

Fig 235
Sand dune with a "blow-out" in its top. Near Julesburg, Colorado. (After U S Geological Survey)

The ruins of the once great cities of Nineveh and Babylon are largely buried under wind-blown sand and dust. Evidence has been presented to show that the climate of western and central Asia is now con-

siderably drier than it was a few thousand years ago. This helps us to understand why so many old villages and cities there have been buried under wind-blown deposits.

Fig 236
Sand dunes near the seashore. Pacific Grove, California. (Photo by the author.)

Loess. — A kind of deposit of special interest, which is mainly or partly of wind-blown origin, is called *loess*. It is usually a fine grained, unstratified, yellow to brown loam or silt which, though very slightly consolidated, has the remarkable property of standing in the form of high, very steep slopes or cliffs where it has been cut into by erosion (Fig. 237). It sometimes contains shells of land animals. It forms extensive deposits, commonly from 10 to several hundred feet thick, in various regions

Fig. 237
A roadway through a deposit of loess in China Note the vertical structure. (Photo by Bailey Willis for the Carnegie Institution of Washington.)

Certain valleys of northern Europe, especially the Rhine, contain loess deposits. Extensive deposits occur in Argentina. Thousands of square miles in Iowa, Nebraska, and Kansas (particularly in the Missouri and Mississippi Valleys) are covered with loess which is seldom more than 100 feet thick. This is believed to represent the fine loose material blown by the wind from the adjacent regions just after the withdrawal of one of the great glaciers of the Ice Age. The loose glacial soils were then

protected by little or no vegetation. Many thousands of square miles of northern China are covered with loess, much of which may have been blown from the Mongolian desert. It covers both mountainsides and valleys to depths probably as great as 1000 feet. Some of this loess has probably been reworked and deposited by water.

CHAPTER X

THE SEA AND ITS WORK

Extent and Depth of the Sea

It is well known that the waters of the sea cover nearly three-fourths of the surface of the earth. The sea is about 45 times as large as the United States, that is, it covers approximately 140,000,000 square miles. The average depth of the oceans of the earth is about two and a half miles. If the sea were present universally, everywhere with the same depth, it would be almost two miles deep. Yet this vast body of water is an extremely thin layer when compared to the earth's diameter of nearly 8000 miles.

The Pacific is the deepest of the oceans, its average depth being about two and three-quarters miles. The deepest sounding ever made was 32,644 feet, or over six miles, about 145 miles southeast of Tokio. The second deepest place is 32,114 feet, not far from the Philippine Islands. It is called the Planet Deep. In the Pacific Ocean there are six places where the water is over five miles deep, and 11 places where it is over four miles deep. The deepest sounding ever made in the Atlantic Ocean was 27,972 feet, not far from Porto Rico.

Composition of the Sea Water

Many substances are known to be in solution in sea water, but, in spite of this, the composition is remarkably uniform. The most abundant substance by far in solution is common salt. In every 100 pounds of sea water there are three and one-half pounds of mineral matter of various kinds dissolved. Nearly 78 per cent of the dissolved matter is common salt. The other principal constituents in solution are chloride and sulphate of magnesia, and the sulphates of lime and potash. All other dissolved mineral substances together make up less than one per cent of the total. It has been estimated that if all the dissolved mineral matter in the sea could be brought together it would form a layer 175 feet

thick over the whole sea bottom The salts of the sea have been mostly supplied by the rivers which in turn have derived them from the disintegration and chemical decay of the rocks.

In addition to the salts in solution, there are certain gases, chiefly atmospheric, that is, they have been dissolved mostly from the air. Organisms and submarine volcanoes supply some gases. The principal gases in solution are nitrogen, oxygen, and carbonic acid gas

Temperature of the Sea

The temperature of the surface sea-water in the torrid zone is from 75° to 80° From this there is a fairly gradual decrease to about 28° in the polar regions The freezing point of sea water is 28° instead of 32° as for fresh water. Many variations in the temperature of the surface sea-waters are due to ocean currents.

In the torrid and temperate zones, at depths greater than 4000 to 5000 feet, the temperature of the sea is always lower than 40°. Fully two-thirds of the ocean water is, therefore, colder than 40°, and the water grows colder with increasing depth, even reaching 31° at great depths. At the greatest depths under the equator, the water is not far from the freezing point. In the polar regions the sea is of course, from surface to bottom, nearly everywhere at or near the freezing point.

Life in the Sea

Both plants and animals exist in countless numbers in the sea. The animals range in size from single-celled microscopic forms to that of the whale. Lower orders of animals are much more common than the higher. Among the higher forms of animal life are whales, seals, walruses, turtles, and untold millions of fishes. The plants are mostly simple forms, like seaweeds, which range in size from microscopic to several hundred feet long.

In the upper few hundred feet of the sea, and more especially at and close to the surface, vast swarms of organisms, both plant and animal, exist. Most of these are tiny to microscopic in size. Since plants depend upon light for their existence, they are confined wholly to the upper few hundred feet of the sea

Murray, the great student of the ocean, says: "We know that the whole of the surface waters of the ocean are crowded with

minute unicellular algae (seaweeds, etc.) which are ever busy, under the influence of sunlight and chlorophyll, converting the inorganic substances in the sea water into organic compounds, which in turn supply not only the food of the vast majority of marine animals which live in the surface and intermediate waters, but also of the myriads of creatures living near and on the sea floor, miles beneath the level to which the sun's rays can penetrate. . . . The bodies of the minute unicellular algae, which often have calcareous, siliceous, or chitinous shells, fall to the bottom after death, together with the dead bodies of the animals which browse in the meadows; accumulating on the surfaces of the deep-sea oozes and clays, they supply nourishment for the creatures that crawl on the bottom of the sea"

Besides the minute forms there are "many larger floating and swimming species, and some clinging and fixed forms attached to floating bodies such as logs and seaweeds, or to swimming animals. In the (so-called) Sargasso Sea, for example, there is a miniature world of plant life and dependent swimming, crawling, and fixed forms of animal life. Among the larger animals are numerous fishes, some like the herring and mackerel, swimming in great schools, others moving singly like the shark and swordfish. The whale also roams in the surface and upper layers of the ocean. A multitude of floating species of jellyfish and other forms of animal life also inhabit this zone" (Tarr and Martin).

Compared to the countless myriads of organisms in the upper layer of the sea, the animal life of the great bulk of ocean water is much less profuse. Deep-sea investigations have, however, revealed the existence of many types of animals. Many of these are very curious-looking creatures with no counterparts in the land waters. Some of them, like the so-called "sea lily," belong to types of geologically old animal forms as proved by the remains of similar creatures embedded in the rocks of the earth. Prominent among the swimming creatures of the deep sea are certain strange-looking fishes. Other types of animals either crawl on the sea-bottom or burrow through the soft, oozy substances there.

Along the seashore, and in the shallow waters near shore, especially in the warmer zones, animal life is abundant and varied, including many shelled forms, such as clams, mussels, and barnacles; crustaceans, such as lobsters and crabs; so-called starfishes of various sorts; and, in clear waters not colder than 68°

corals. In many places, as for example around Florida, and just north of both Cuba and Australia, the corals have built up great reefs by the accumulations of the carbonate of lime skeletons which these tiny animals have secreted from the sea water.

Tides

The tide is a great wave hundreds of miles across, and only a few feet high in the open ocean. It is caused chiefly by the attraction of the moon, and to a slighter degree by the sun. The highest wave results when the sun and moon pull together along the same line. Since there is a reaction about equal to the action on opposite sides of the earth, two tidal waves are produced at the same time. Because of the earth's rotation, were there no lands to interfere, each of these great, low waves would pass around the earth every 24 hours, or, in other words, one would pass a given place every 12 hours. As it is, a tidal wave strikes the shore of each hemisphere every 12 hours, the water piling up on the shore until the crest of the wave comes, after which the water recedes gradually. In bays and estuaries, especially those which are V-shaped with their wide portions toward the ocean, there is a tendency for the water to pile up unusually high. A very remarkable example is the Bay of Fundy, in which the tidal wave often rises 30 to 50 feet.

Ocean Currents

In the equatorial regions of both the Atlantic and Pacific Oceans, the steady friction of the persistent trade winds produces wide, westward moving, surface currents. Each of these currents, on striking the continental coast, divides into two portions, one moving southward and the other northward. Each portion then crosses the ocean eastward and finally turns back into the equatorial belt. Thus there are in each great ocean two vast eddies, one north, and the other south, of the equator, with relatively quiet water in the midst of each. When a wide, slow current approaches the land, its water tends to accumulate and, where the slope of the land is favorable, it becomes narrower and swifter, giving rise to so-called *streams*.

The *Gulf Stream* is formed by a crowding of part of the deflected equatorial current of the Atlantic into the Caribbean Sea and the

Gulf of Mexico. Where it emerges from the narrow strait between Florida and Cuba, it has a speed of 100 miles per day. As it moves along the eastern side of the United States, and into the Atlantic Ocean, it becomes gradually much wider, and its velocity is reduced to about 10 miles per day.

Topography of the Sea Floor

If we make a general comparison with the surface of the land, the bottom of the ocean is a vast monotonous plain. None of the sea bottom compares with the ruggedness of the mountains, and even the more level portions of the land surface nearly always show many sharp, minor irregularities, such as stream trenches; but the sea bottom is characterized by its smoothness of surface. Under the sea there are, however, mountain-like ridges, plateaus, submarine volcanoes, and valleys, the deeper valleys being known as *deeps*, but such features rarely, if ever, show ruggedness of relief like similar features on land.

One of the most remarkable relief features of the ocean bottom is the so-called *continental shelf*. It is a relatively narrow platform covered by shallow water bordering nearly all the important lands of the earth. Usually the water increases in depth seaward over this platform, but it seldom exceeds a depth of 600 to 800 feet (Fig. 238). The continental shelves of the world cover about 10,000,000 square miles, or about one-fourteenth of the area of the sea floor.

On the way from New York to Europe, a ship sails over the continental shelf for about 100 miles, the water gradually increasing in depth to less than 1000 feet. Then there is a comparatively steep descent (called the *continental slope*) into the great *ocean abyss* which is two to three miles deep. The floor of this abyss is a vast monotonous plain stretching across the Atlantic almost to the shores of Europe. A little more than half way across, the ocean bottom rises as a kind of plateau or ridge a few hundred miles wide, with water not more than one to two miles deep over it. This submarine ridge runs roughly north and south with a winding course through nearly the whole Atlantic Ocean. Within a few hundred miles of Europe the sea bottom begins to rise on a continental slope to a continental shelf which, with its shallow water, extends to the shore.

Waves

There are several kinds of sea waves, such as wind waves, tidal waves, earthquake waves, etc. Our present concern is with wind waves, which are produced by the friction of wind blowing over the sea surface. Since important work of marine erosion is accomplished by waves, certain facts regarding them should be known

It is an interesting fact that, in calm weather, the form of a wave advances, but the water does not. This is because the wave form is caused by particles of water moving in vertical, circular orbits. A familiar demonstration of this fact is the rising and falling, and to and fro movement, of a chip when small waves pass under it on a pond in clear weather The chip does not move forward, but the wave forms do.

When a wave moves into shallow water on a gently sloping bottom, the lower part has its motion gradually checked so that the unimpeded upper part rushes over it forming a *breaker*. After a breaker rushes upon a sloping shore, the water returns down the slope with development of an undercurrent called the *undertow*.

If a wave strikes the shore obliquely, the undertow moves down the slope at right angles to the shore, and the next wave drives part of this same water against a slightly different part of the shore. Repetitions of this process cause the development of a *shore current* whose strength may be augmented by the prevailing wind These shore currents are, as pointed out beyond, important in the building of certain shore forms

Storm waves on the sea are commonly from 15 to 20 feet high, and several hundred feet long, but they may at times be twice that size Such waves attain velocities of from 20 to 60 miles per hour.

In considering the work done by waves, it is important to know that large waves will move coarse sand and gravel at depths of from 50 to 100 feet, and fine sand at a depth of several hundred feet.

The force with which waves strike bold, rocky shores is also an important consideration because of its influence in wave erosion (Fig. 239). The force of impact of waves is ordinarily from 1000 to 2000 pounds per square foot, but in great storms it is several times as much when blocks of rock many tons in weight are moved.

Marine Erosion

How Waves Erode. — When a wave dashes against a rocky shore or cliff, water is forced into many cracks and other openings, causing a hydrostatic pressure which tends to disrupt blocks of rock in the face of the cliff. Also many fissures and crevices are suddenly filled with compressed air which, on retreat of the wave, has its pressure relieved quickly, thus producing a so-called "suction" which often dislodges masses of rock. The very impact of the wave against a shore may be sufficient to force off rock material from a cliff, not only of soft or loose rock, but also of hard rock if there are masses of it already sufficiently loosened by jointing or weathering. A minor factor in the removal of rock material by waves is the solvent action of sea water.

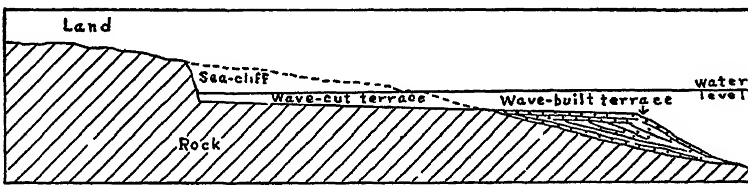

Fig. 238

Diagrammatic structure section illustrating the development of the sea cliff, wave-cut terrace, and wave-built terrace (Drawn by the author.)

Waves are most effective as agents of erosion through their grinding action. Waves, like running water, wind, and glaciers, erode most effectively when properly supplied with rock fragments as tools with which to work. When strong waves, armed with rock fragments already dislodged from the shore, repeatedly strike a rocky shore or cliff, they become powerful agents of shore destruction. Even the hardest rocks must yield to such abrasive (or corrasive) action. Such battering of the rock fragments of all sizes, and their rubbing against one another when carried by the undertow, soon cause the fragments to become rounded (Fig. 240). The older fragments are worn down from pebbles and boulders to fine sand and mud, while new fragments are being derived from the shore. In high latitudes, when shore ice, containing many rock fragments, breaks up and is driven against the shore by wind and storm waves, it becomes an important factor of erosion.

Sea Cliff and Wave-cut Terrace. — Where waves are at work cutting into a shore of at least moderately high land, a steep front facing the sea soon develops. This is called the *sea cliff*. At first the waves may attack the whole face of the cliff, but after a time the cliff becomes so high that the waves attack only its lower portion. By this undercutting process, aided by weathering, the material from the higher portion of the cliff breaks away and falls to the base to furnish more tools with which the waves may batter the cliff. It is by the process just outlined that the sea cuts its way horizontally into the land.

Fig. 239
Sea waves eroding a rocky coast. Santa Cruz, California (Photo by the author)

As the sea cliff retreats, a shallow-water shelf, called the *wave-cut terrace* (Fig. 238) develops, over which the water increases in depth seaward to the limit of wave action, that is, to a depth of hundreds of feet. Such a terrace will not, as a rule, be cut many miles wide because the waves, in moving over the shallow-water shelf, lose their power gradually on account of friction on the bottom. With a slow sinking of the coast, a much wider wave-cut terrace may of course be produced by wave erosion.

Much material cut away and ground up by the waves is carried seaward usually to build up the *wave-built terrace* (Fig. 238), which is something like a submarine delta. Some of it is carried by shore currents to form spits, bars, etc., as explained beyond.

Rate of Retreat of Sea Cliffs. — The rate of retreat of sea cliffs is known in many places. The rate is of course dependent upon various factors, particularly the force and persistence of wave action, and the nature of the rocks attacked. A cliff of loose material is cut back often so rapidly as to be a matter of common knowledge. A remarkable example is the island of Heligoland on which, until recently, was located the powerful

German fort, guarding the Kiel Canal. In the year 800 A.D., this island had 120 miles of shoreline; in 1300 it had 45 miles of shore; in 1649 only eight miles; and in 1900 only three miles.

In southeastern England "whole farms and villages have been washed away in the last few centuries, the sea cliffs retreating from 7 to 15 feet a year." A church located a mile from the seashore near the mouth of the Thames in the 16th century now stands on a cliff overlooking the sea.

Fig. 240
Sea cliff with wave-worn boulders at its base Near San Pedro, California. (Photo by the author)

An island of soft-rock material in Chesapeake Bay covered over 400 acres in 1848, and the waves reduced it to about 50 acres by 1910.

Certain cliffs of soft material on the island of Martha's Vineyard retreated five and one-half feet per year between 1846 and 1886. Wave erosion on very hard rock, like granite, is far less rapid.

Sea Caves, Coves, Stacks, and Arches. — Many irregularities are often developed during the retreat of the sea cliff and the

cutting of the wave-cut terrace. *Sea caves* are often produced along the bases of cliffs by wave action, especially where masses of weaker rocks lie at or near sea level.

If, along a coast, masses of more easily eroded rocks are separated by harder or more difficultly eroded rocks, the waves will cut the former back faster to form *sea coves*, while the latter project into the sea to form *headlands*.

If part of the roof of a sea cave collapses, or if two caves on opposite sides of a sharp headland unite, a *sea arch* results (Fig. 242) The waves will continue to batter the arch until it collapses.

Fig 241
Horizontal strata being irregularly cut into by sea waves Near Laguna, California. (Photo by the author.)

Unequal wave erosion along a rocky coast often leaves isolated portions of cliffs known as *stacks* (Fig. 243). They are at most very temporary objects. A famous example is the Old Man of Hoy in the Orkney Islands. It is an isolated joint column of colored sandstone 600 feet high. Many examples of stacks occur on the New England coast, and on the Pacific coast of North America.

Plains of Marine Erosion. — With sufficient uplift of land relative to sea level, a wave-cut terrace becomes a *plain (or terrace) of marine erosion*. The surface of such a plain, like that of a stream-developed peneplain, cuts across all kinds of rocks irrespective of their composition and structure. On a peneplain, however, the rock waste is characteristically a residual soil, while that of a plain of marine erosion consists of water-worn transported material rather uniformly spread over the surface. The surface of a newly upraised marine plain is usually smoother than that of a plain of stream erosion, and the erosion remnants left by the waves are steeper sided than those on a peneplain formed by streams. A remarkable example of a long plain of marine erosion with

steep-sided, isolated masses (former islands) rising above its surface occurs on the eastern side of India.

A conspicuous marine terrace, usually with an altitude of approximately 100 feet, faces the sea at many places along several hundred miles of the coast of southern California. Still higher terraces, proving successive uplifts of the sea floor, are also well preserved along parts of this coast.

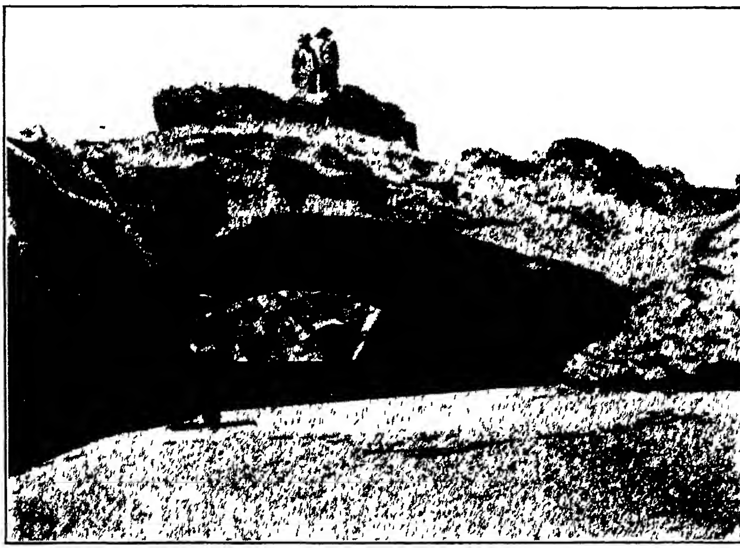

Fig. 242
A natural bridge carved out by high-tide waves Santa Cruz, California. (Photo by the author.)

Southern New England in general slopes from Massachusetts southward to tide water, but it does so by a series of more or less well-defined, broad, steplike platforms. It has been advocated recently that these platforms represent marine plains or terraces raised out of the sea by successive movements in relatively recent geological time. In this region the surface of the terraced plain, being older, has been much more modified by weathering and erosion than that around Los Angeles.

Before leaving the consideration of marine erosion, mention should be made of the fact that, during the long eons of earth

history, the sea has been a much less important factor in cutting away the lands than the subaerial agents of erosion, particularly streams. Subaërial agents of weathering and erosion operate incessantly over most of the land surfaces, while marine erosion is restricted to the margins of the lands, and, as a matter of fact, only to parts of the land margins because, in many places, marine deposition, rather than erosion, is taking place along coasts. "At the rate of five feet per century — a higher rate than obtains on the youthful rocky coast of Britain — it would require more than 10,000,000 years to pare a strip 100 miles wide from the margin of a continent, a time sufficient, at the rate at which the Mississippi Valley is now being worn away, for subaërial denudation (erosion) to lower the lands of the globe to the level of the sea" (W. H. Norton).

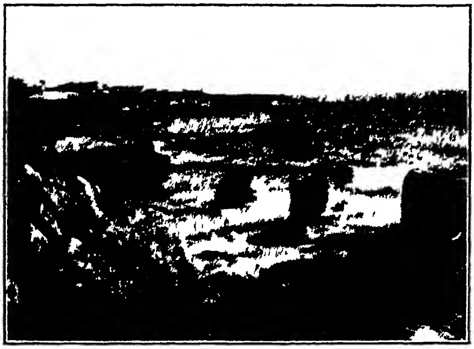

Fig 243
Remnants of wave erosion (so-called "stacks") La Jolla, California. (Photo by the author)

Marine Deposits

~~Viewed in a broad way~~, there are two ~~great~~ ~~classes~~ of marine deposits: (1) those laid down in shallow water comparatively near the borders of the land, that is, on the continental shelf and continental slope; and (2) the abysmal (deep sea) deposits laid down on the floor of the deep ocean.

Shallow-water Deposits. — *General statement.* Marine sediments which accumulate along and near the continental borders are largely land-derived materials, that is, they are mostly sediments carried by streams from the land into the sea, and to a less extent rock materials broken up by the waves along many shores. Practically all land-derived material is deposited within 100 to 300 miles of the shore. The quantity of such sediment carried into the sea each year is tremendous. Thus the Missis-

sippi River carries several hundred million tons of sediment into the Gulf of Mexico each year.

The continental border deposits are extremely variable. Near the shore they are chiefly gravels and sands, while farther out they gradually become finer, and on the continental slopes only muds are deposited. These deposits usually contain more or less organic material, especially shells and skeletons of organisms In some cases such organic remains predominate, or even exist to the exclusion of nearly all other material, as is true of the coral deposits (or reefs) which form only in warm, shallow water.

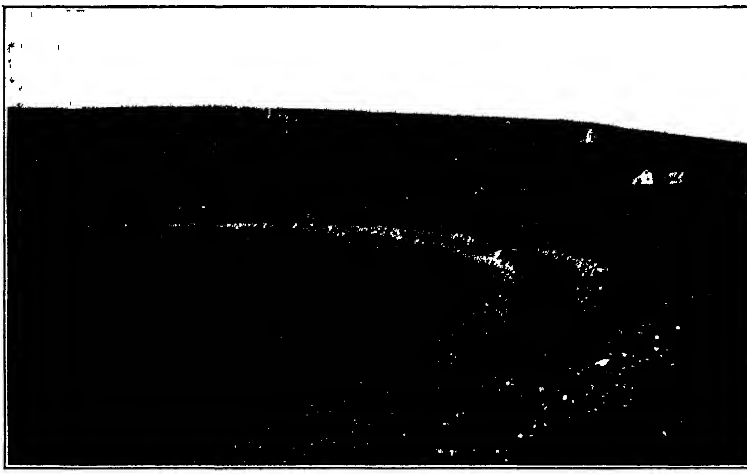

Fig 244

A crescentic gravel beach. Conception Bay, Newfoundland (Photo by C D Walcott for U. S. Geological Survey.)

Materials which accumulate on the shallow-sea bottom around the borders of the lands are of great significance to the geologist because just such marine deposits, now consolidated into sandstones, conglomerates, shales, and limestones, are so widely exposed over the various continents. A knowledge of the conditions under which shallow-sea deposits are now forming is, therefore, of much value in interpreting events of earth history as they are recorded in similar rocks which have been accumulating through millions of years of time, and which have, from time to time, been raised into land, and more or less eroded.

Beaches and barriers. The loose material, ranging in size from very fine to large boulders, which is shifted and ground up by the action of the waves, undertow, and shore currents, is called the *beach.* It consists of the zone of rock fragments within reach of the waves along the shore. "Its lower margin is beneath the water, a little beyond the line where the great storm waves break. Its upper margin (on shore) is at the level reached by storm waves, and is usually a few feet above still water" (Chamberlin and

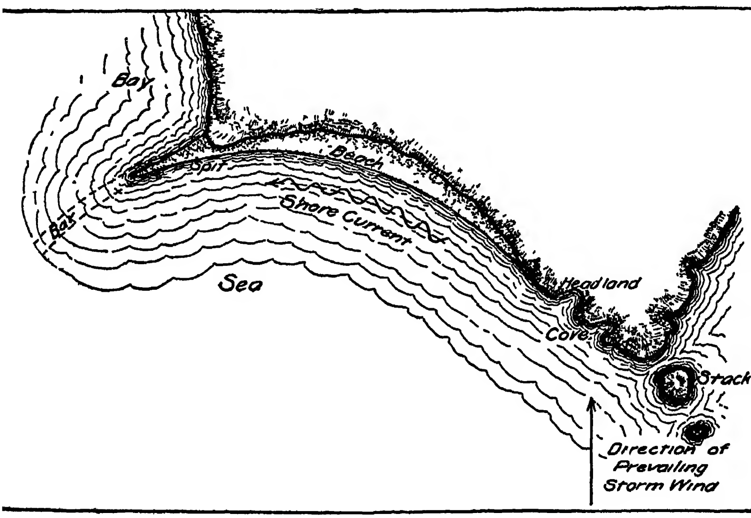

Fig 245

Sketch map illustrating erosion of a headland and development of a shore current, beach, spit, bar, cove, and stacks (After W H Hobbs)

Salisbury). The upper portion of the beach consists generally of coarser material, while its lower, or constantly under-water portion, is made up of finer material. Beaches are, as a rule, not prominently developed at the bases of sea cliffs, but (except along very young coasts) they are well-developed generally around the shores of coves and recesses of the coasts (Fig. 244). Where the land slopes down to the sea gently, as on coastal plains, beaches are often also finely developed.

Where the sea bottom slopes very gently from the shore, materials which are derived by inflow of streams, and spread over

the bottom by currents and undertow, may be acted upon by waves which drag the bottom and break some distance from the shore. The breaking of such waves causes the water (not merely the wave form) to rush forward, stirring up and dragging along

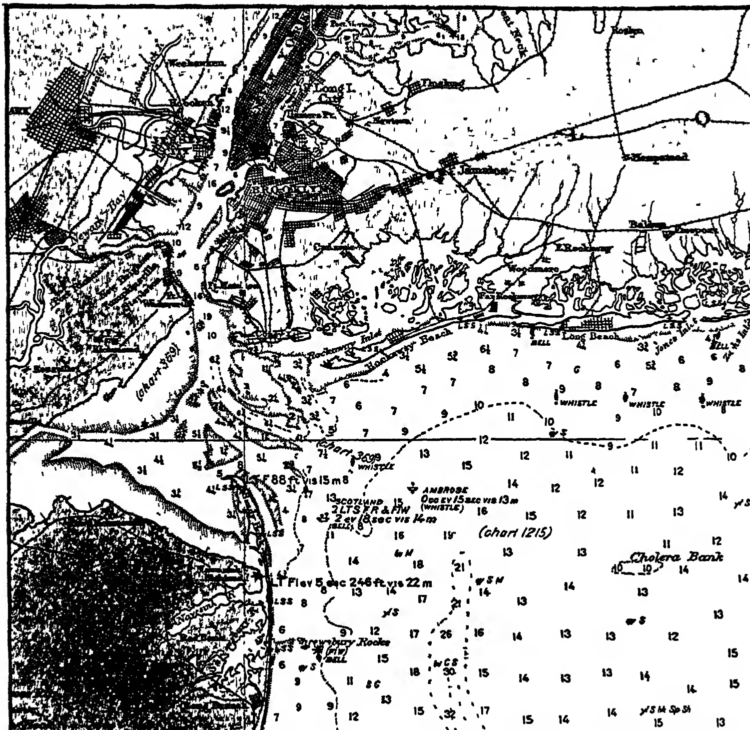

Fig 246

Map showing beaches and spits near New York City in 1916. Figures represent depths in fathoms below low tide. (After U. S Coast and Geodetic Survey)

sediment. The undertow carries back much of the material which tends to accumulate in an offshore zone where the forward rush, and the reversed undertow movement, about counter-balance. A long *barrier beach*, or a series of *barrier islands*, thus builds up some distance out, parallel to the general coast line (Fig. 247).

A barrier beach may be built up to the surface of the water by wave action, and then increased in height by wind action, forming the sand into dunes. Such barrier beaches are prominently displayed along the Atlantic and Gulf Coasts of the United States from New Jersey to southern Texas.

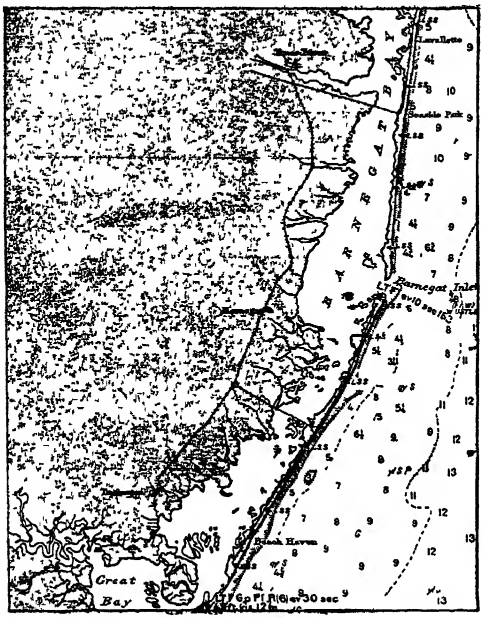

Fig 247
Barrier beaches along the New Jersey Coast in 1916. Depths in fathoms below low tide. (After U S Coast and Geodetic Survey.)

The water of the area between the barrier and the shore is called a *lagoon* or *sound*, depending upon its size. Its water is seldom more than 10 or 20 feet deep. Lagoons are often converted partly into marshes either by accumulation of sediment from the land, or by vegetation, or by both. Atlantic City, New Jersey, is built upon a barrier beach bordering such a lagoon.

Spits and bars. When a shore current, carrying sediment, comes to a cove or a narrow embayment on the coast, it tends to keep to its course rather than to follow the shore of the embayment. The sediment-laden shore current thus moves into deeper, quieter water where its load is deposited, and thus a *spit* builds out from the shore (Fig. 245). When the current moves across the mouth of an embayment, the spit may continue to extend until it nearly, or quite, closes the embayment. It is then called a *bar* (Fig. 249).

Deltas. The building of deltas, often of large extent, into the sea (or into lakes) by rivers, under certain conditions, has already been considered in the discussion of stream deposition in Chapter

VII. Sea deltas are built of land-derived materials carried in by rivers, but they may be regarded, in a real sense, as marine deposits because they build out into the sea

Wave-built terrace. Where sea cliff and wave-cut terrace are both being eroded by wave action, the loosened materials are

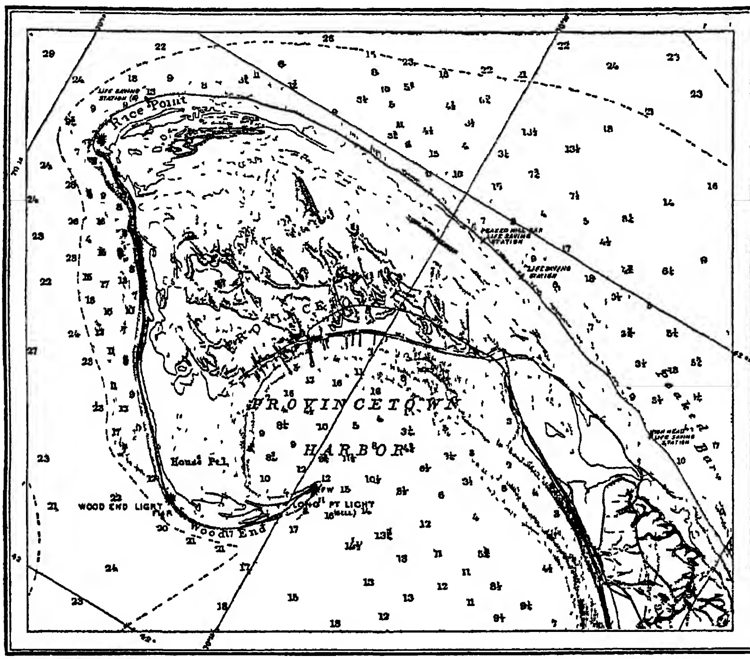

Fig. 248

Great curved spit at the end of Cape Cod, Massachusetts Figures show depth of water in fathoms (After U. S. Coast and Geodetic Survey.)

ground up and, in large part, may be gradually shifted over the bottom to the deeper water at the seaward edge of the wave-cut terrace, and there deposited. A very considerable *wave-built terrace* may be formed by this process in the course of time (Fig. 238). The continental shelf is often a combination of wave-cut and wave-built terraces.

Shallow-water features, such as sea cliff, wave-cut terrace,

beach, barrier, bar, and spit, are often preserved for some time after elevation of the shallow sea-bottom into land

Deep-sea Deposits. — The deposits on the deep-sea bottom, down to depths of two and three miles, are very largely organic, that is, mainly shells and other remains of organisms which have fallen to the bottom from near the surface of the sea as already explained. The most common of such deposits are the deep-sea *oozes* which are made up of the remains and shells of tiny animals and plants. Such oozes cover about 60,000,000 square miles of the deep-sea bottom.

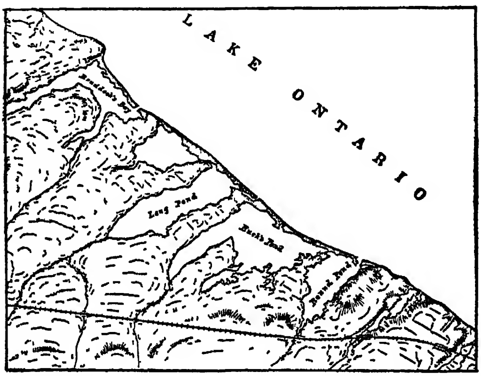

Fig 249

Bars almost completely enclosing embayments of Lake Ontario (After U S Geological Survey.)

At depths greater than two to three miles, a peculiar red clay is the primary deposit. It is very widely distributed, covering an area of 55,000,000 square miles, or an area as large as all the lands of the earth. Some remains of organisms are mixed with the clay, but since most of the shells are limy and very thin, they are dissolved without reaching the bottom in the very deep water which is not only under great pressure, but also rich in carbonic acid gas.

The deep-sea deposits, both oozes and red clay, do, however, contain some land-derived and other materials. Thus off the west coast of Africa some dust from the Sahara Desert is known to fall into the deep sea. Volcanic dust is often carried many miles, and deposited in the deep sea, particularly in the southern Pacific Ocean. Bits of porous volcanic rock called *pumice* sometimes float long distances on the ocean before becoming sufficiently water-soaked to sink. Icebergs often drift far out from the polar regions over the sea, and, on melting, the rock débris which they carry is dropped to the sea bottom. Also particles of iron and

dust from meteorites (" shooting stars ") have been dredged from the deep sea.

One important geological significance of the abysmal deposits is the fact that nowhere on any continent, among the rocks of all ages as old at least as the earliest Paleozoic, do we find any typical, deep-sea deposits. There is, therefore, no evidence that deep-sea water ever spread over any considerable part of any continent, and this is so in the face of the fact that abundant marine deposits of shallow-water origin show that shallow seas have at various times spread over large portions of continents. There has been, then, a strong tendency for the continents to maintain approximately their present positions for many millions of years.

Normal Cycles of Shoreline Development

Cycle Inaugurated by Uplift. If a part of the relatively smooth sea-bottom should be raised into land, the resulting shoreline would of course be regular and free from indentations or sharp embayments. Examples of very young coasts of this kind are: near Cape Nome, Alaska; the northern coast of Spain; and the west coast of northern South America. Soon, however, such a shoreline, where the water is sufficiently deep offshore, is attacked and, either where the waves are greatest or the rocks are weakest, indentations will result from erosion. The whole coast is thus eaten back gradually until the power of the waves is spent largely in traveling across the shallow-water shelf. Sand bars are then built across the mouths of the bays or indentations, which latter the rivers fill gradually with sediment. The result is

Fig. 250

A marine terrace (with "stack") being cut into by sea waves. Near Pismo, California. (Photo by the author)

a relatively straight, or regular, old shoreline. The coast of Texas has almost reached this stage. Where, along a newly uplifted coast, the sea bottom slopes very gently, erosion will amount to little or nothing, and beaches or barriers will develop without disturbing notably the original regularity of the uplifted coastline.

Cycle Inaugurated by Subsidence. — If a portion of a relatively rugged land surface should become submerged under the sea, a very irregular, deeply indented shoreline would result, due to the entrance of tide water into the valleys. Such drowned

Fig. 251

A fiord. Grenville Channel, British Columbia. (Photo by W. W. Atwood for the U. S Geological Survey)

valleys (p. 190) become *estuaries*, or, if they are unusually deep and narrow as a result of glacial erosion, they become *fiords* (Fig. 251). Chesapeake Bay and Delaware Bay are good illustrations of estuaries, and fine examples of fiord coasts are in Maine, Alaska, and Norway Such a sunken coast is attacked by the ocean waves which at first make it rougher and even more irregular. Then the promontories are cut back until the broad shallow-water shelf is formed, after which bars are built across the remaining embayments, and the shoreline becomes relatively

regular. Submergence of a smooth land area would of course result in a regular shoreline which would at first become more or less irregular and indented, and then again regular through wave action, according to the depth of the water off-shore. It is, then, a remarkable fact that, whether coast forms originate by emergence of sea bottom, or by sinking of land, there is a very strong tendency on the part of nature to develop regular shorelines.

Comparison of Coastal and River Cycles. — "There are several points of similarity between coastal cycles and the erosion cycles of rivers First a river system roughens the surface of its basin, increasing its relief; finally it reduces it to a smooth plain, near sea level. As indicated above, waves and currents normally increase to a maximum the irregularities of a coast, and finally reduce them to a minimum. An essential difference is that the irregularities of the river basin are vertical irregularities, while those of the shoreline are horizontal. In each case the cycle of development is introduced by diastrophism." (Blackwelder and Barrows).

It must of course be borne in mind that the normal cycles of shore development, like those of river erosion, are often interrupted either by uplift or by sinking of the land. It would involve us in too much detail, for our present purpose, to discuss the various important changes which result from such interruptions by diastrophism.

Islands in the Sea

Sea islands range in position from those very close to shore to others which lie in the midst of a great ocean. They vary in size from mere points of rock to those of very great size, for example Australia, which may be said to have continental dimensions.

Among the most common modes of origin of sea islands are: earth-crust movements; wave erosion; wave deposition; volcanic action; and the action of organisms. Brief explanations of a few examples will serve to make the involved principles fairly clear.

Fine examples of islands formed by earth-crust movements are those off the coast of southern California. They were parts of the mainland until in very recent geological time (present period), as proved by fossil remains, etc., when they were separated by a general submergence of the region, leaving the higher seaward

portions projecting as islands. Since then they have been affected by other movements, as for example San Clemente which has been elevated hundreds of feet (Fig. 62). Many of the islands along the coast of Maine and of southern Alaska are direct results of general coastal subsidence. The great island of Australia was cut off from the Asiatic Continent about the beginning of the present (Cenozoic) era, as proved by a comparison of the fossils of the island with those of the adjacent mainland. All such islands have of course been attacked and modified more or less by wave action.

Many islands, generally of small size have originated by isolation of parts of a rugged coast by wave erosion, as already

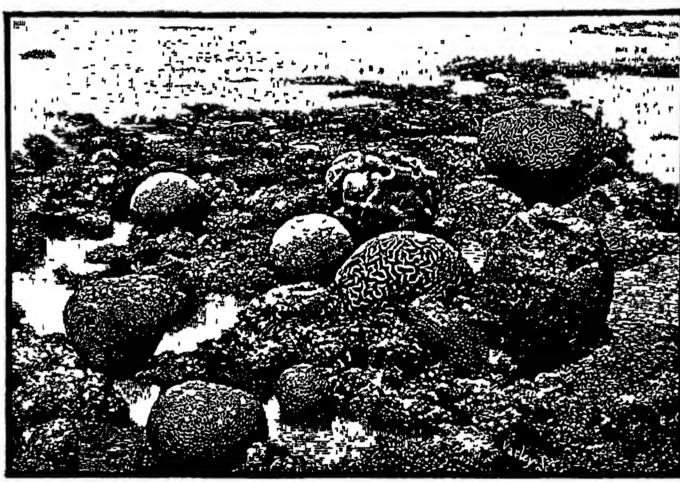

Fig. 252
Part of a great coral (barrier) reef of Australia at low tide. (After W. M Davis.)

outlined. Sometimes the neck of a headland, or even a peninsula of considerable size, may be cut through by wave action, leaving an island. Many examples occur off the coast of Maine and southern Alaska where islands and headlands resulting from submergence have been thus affected.

Relatively long, narrow islands, called barriers and barrier islands (already described), result from wave deposition off-shore

where the bottom is very gently inclined seaward. Numerous examples occur on the Atlantic and Gulf Coasts of the United States from New Jersey to southern Texas.

Eruptions on the sea floor may continue not only until the volcanic materials are built up to, but also far above, the surface of the sea. Wonderful examples of islands thus constructed are the Hawaiian Islands which rise out of the midst of the Pacific Ocean where the depth of the water is several miles. One of these islands is about 80 miles wide with two volcanic cones, each nearly 14,000 feet high. The total up-building by volcanic action to form this island has been, therefore, fully 30,000 feet. The Azores, most of the West Indies, the Aleutian Islands, and many of the East Indies are also islands of volcanic origin.

Oceanic islands formed by the action of organisms are mainly *coral islands*. Corals are tiny, low-order animals which build up limy skeletons by secretion of lime which is dissolved in sea water. Under favorable conditions, countless myriads of corals live in colonies. Extensive limestone deposits are formed by the gradual accumulation of their skeletons. Corals live only in clear sea water, not cooler than 68° F., and not much deeper than 150 to 200 feet. They thrive best where freely exposed to waves and currents which supply the food.

Chains of islands, or long, narrow belts, consisting of accumulated coral remains are called *coral reefs*. The greatest reefs are hundreds of miles long, as for examples on the northern side of Cuba, and on the northeastern side of Australia (Fig 252). A coral reef attached to the shore is called a *fringing reef;* one situated offshore some distance, and roughly parallel to the shore, is called a *barrier reef;* and a more or less circular reef enclosing a lagoon is called an *atoll*.

Several explanations of barriers and atolls have been propounded. Thus a fringing reef attached to a roughly circular island would, by slow subsidence, accompanied by coral up-building, be transformed into a barrier reef, which on complete sinking of the island, would become an atoll. Or, corals growing on any submerged platform, or island truncated by the waves, would build upward and outward (because of more favorable food supply) to the sea surface to form an atoll. A barrier reef might develop also parallel to a shore without subsidence. In this case a fringing reef might build steadily outward and upward from near the

shore, while the portion between its outer side and the shore, not favorable to coral growth, would be scoured out and dissolved by tidal currents.

Corals can build reefs to about the average tide level only. Storm waves may break off pieces of the reef and pile them up well above sea level. Such material may then be built up into wind-blown deposits still farther above sea level, as in the case of Bermuda. Coral islands of all kinds and sizes are very common in the southern Pacific Ocean.

Origin of the Sea

Just how the sea originated is a problem by no means satisfactorily solved. Any view which we may hold regarding the origin of the ocean must be associated closely with, and largely dependent upon, our view of the origin of the earth itself.

An older doctrine, known as the "Nebular Hypothesis," regards all the material of the sun and the planets, including the earth, once to have been in the form of a vast rounded mass of highly heated, rapidly rotating gas or nebula As this mass slowly lost heat, it contracted and left off rings, the material of each of which condensed to form a planet. Thus the earth originated, and, due to its cooling and contraction, its original, hot, heavy atmosphere, which contained all the earth's water in the form of vapor, gradually became thinner and cooler. According to this view, the waters of the sea are essentially condensed, originally highly heated gas.

A more recent doctrine has been called the "Planetesimal Hypothesis" According to it the matter of the sun and planets was at one time in the form of a great spiral-shaped swarm of masses and particles not in a gaseous condition. A few of the larger masses attracted gradually, or gathered to themselves, most of the smaller ones, and thus the planets, including the earth, were built up. As the earth increased in size, the force of gravity increased, and various gases, including water vapor, were squeezed out to form the atmosphere. When sufficient water vapor accumulated, precipitation started, and the waters of the sea began to gather. According to this view, the waters of the sea have been forced out of the earth.

Although the origin of the sea is still a problem nevertheless

we do know that the sea has been on the earth for an extremely long time. The age of the ocean must be measured by at least some tens of millions of years. There is evidence that sea water existed in the oldest era known to the geologist, that is at least 50,000,000 years ago.

CHAPTER XI

VOLCANOES

Geological Importance of Volcanoes

A volcano is a vent in the earth's crust out of which hot rocks (either molten or solid) and hot gases issue. In the popular mind, volcanoes take rank among the most important and real of all geological phenomena This is because of both the terrifying grandeur and mighty power of violent eruptions, and their destruction of life and property. Great active volcanoes, like earthquakes, are, however, only relatively minor, outward, sensible manifestations of the tremendous earth-changing forces which operate below the surface. Volcanoes are, from the geological standpoint, much less important than the mighty interior forces which cause the rocks of the earth's crust to be folded and faulted, and large portions of continents to be upraised or depressed. Quantitatively considered, the geological work accomplished by volcanoes is notably less than the work of erosion accomplished by running water

In our study of igneous rocks we learned (p 49) that volcanic action is but one of the two important kinds of igneous activity — *plutonic* and *volcanic* — that is, deep-seated shifting and intrusion of molten materials (magmas) into the earth's crust, but not to its surface; and the eruption (or extrusion) of hot rock materials upon the earth's surface. Even as an igneous agency, volcanic action is quantitatively notably less important than plutonic (deep-seated) action.

In making comparisons like those just stated, we must bear in mind the fact that we are dealing with stupendous forces and tremendous masses of the earth's crust, so that volcanic action is, after all, not only a very conspicuous, but also a really significant, means of changing the face of the earth. The geological importance of vulcanism becomes impressive, indeed, when it is realized that, conservatively estimated, fully 500,000 cubic miles of volcanic rocks have been forced out upon the surface of the earth

during the present era of geological time, and that volcanic action was important during each of the five known great eras. In some cases large mountain ranges, like the Cascade Mountains of Oregon and Washington, have been constructed largely of volcanic materials.

Shapes and Sizes of Volcanoes

A volcano, in its typical form, is a cone-shaped mountain with a pitlike opening, called a *crater*, at the top, through which hot rock materials and gases are ejected. The mountain is,

Fig. 253

Molten lava seething, boiling, and swirling around an island of solid lava. Crater of Kilauea, Hawaii (Photo by L de Vis Norton, courtesy of the National Park Service.)

however, a secondary feature of a volcano. The vent is its essential part Accumulation of volcanic rocks around the vent causes the building-up of the *cone* which is of course only an effect of the volcanic action. Even the great volcanoes started simply as vents or fissures in the earth's crust.

Cones of volcanic origin range in height from a few feet to several miles. Illustrative examples of well-known cones are the following: at Mono Lake, California, where there are cones only

10 to 30 feet high; Cinder Cone in Lassen Volcanic Park, California, 640 feet high; Mt. Vesuvius, Italy, 3880 feet high; Stromboli, about 5000 feet high, as measured from the floor of the Mediterranean Sea on which it stands; Lassen Peak, California (Fig. 278), and Mt. Etna, Sicily, each over 10,000 feet high; Mt. Shasta, California (Fig. 270), and Mt Rainier, Washington (Fig. 188), each rising to over 14,000 feet above sea level, and 8000 to 10,000 feet above the surrounding country, and Cotopaxi (altitude, 19,600 feet), Chimborazo (altitude, 20,500 feet), and Aconcagua (altitude, 23,000 feet), all of which rise 10,000 to

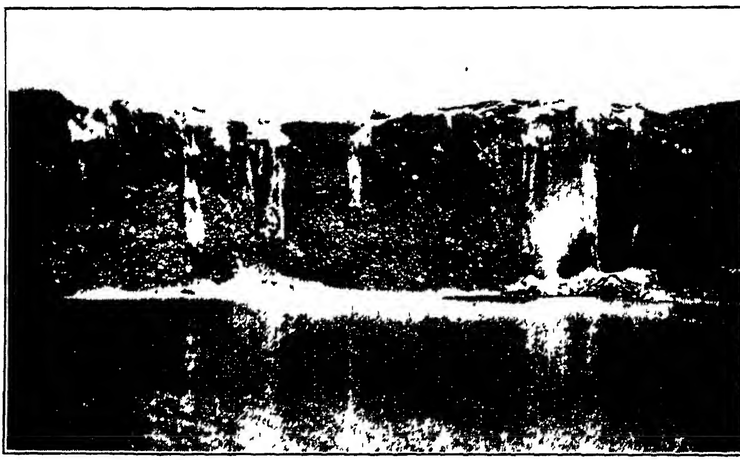

Fig. 254

Molten lava pouring over a cliff into water. Hawaii. (After Diller, U S. Geological Survey)

12,000 feet above the general level of the great elevated platform of the Andes Mountains. Very remarkable cases are Mauna Loa and Mauna Kea on the island of Hawaii, each rising nearly 14,000 feet above sea level, and fully 30,000 feet above the floor of the sea from which they have been built up.

At their bases, volcanic cones are commonly from less than a mile to many miles in diameter. Examples of a few larger ones are: Mt. Rainier, with a basal diameter of over 10 miles; Mt. Shasta, 17 miles; Mt. Etna, 30 miles; and Mauna Loa, with a major diameter of 74 miles, and a minor diameter of 53 miles,

measured at sea level. Mauna Loa is probably the biggest volcanic cone on the earth.

Craters of active, and very recently active, volcanoes range in diameter from a few feet to several miles, and in depth from a few feet to several thousand feet. On relatively older, inactive cones, the craters have of course been partly, or completely, obliterated by erosion. Very large craters, often called *calderas*, have usually resulted either from violent explosions which have caused the tops of great cones to be blown away, or by subsidence of the mountain tops. A few examples of craters are as follows: Cinder Cone, California, a few hundred feet wide, and 240 feet deep; Lassen Peak, one-fifth of a mile in diameter, and a few hundred feet deep; Cotopaxi, one-half of a mile in diameter, and 1500 feet deep; Mauna Loa, about two and one-half miles in diameter, and 1000 feet deep; Katmai Volcano, Alaska, three miles in diameter, and several thousand feet deep; and Mt. Mazama, Oregon, with its famous Crater Lake, nearly six miles in diameter, and several thousand feet deep.

Fig 255
Wavy, porous lava still hot and steaming. Kilauea, Hawaii. (Photo by the author.)

The steepness of the sides of volcanic cones varies from only 5° to 10°, as in the case of Mauna Loa; to 30° or 35°, as in the case of the upper portion of Mt. Shasta; or even to 40° in some recent, so-called cinder cones.

Volcanic Products

Gases and Vapors. — Tremendous volumes of gases and vapors are discharged through volcanic vents. The most abundant by far is water vapor, or steam. The quantitative importance of water vapor as a product of great volcanoes may be realized somewhat by consideration of an estimate that about 462,000,000

gallons of water in the form of steam were discharged in 100 days from a secondary cone on the side of Mt. Etna. Great clouds of steam, usually mingled with more or less volcanic dust, often rise to heights of several miles above large volcanoes during their periods of explosive activity (Fig. 267) Condensation of such steam clouds sometimes causes heavy rainfall in the vicinities of the volcanoes. Much water vapor also escapes from streams of

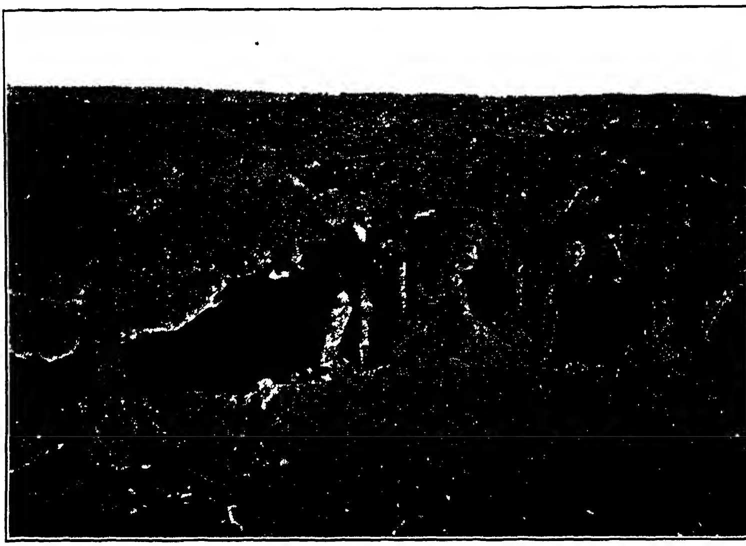

Fig 256
A lava-flow over the edge of an old lava tunnel. Kilauea, Hawaii. (Photo by the author.)

molten lava, and the discharge often continues for weeks, or even months, after the lava solidifies.

Among the many other gases which are given off by volcanoes and lava flows are the following: sulphide of hydrogen, oxide of sulphur, hydrochloric acid, hydrofluoric acid, boric acid, nitrogen, hydrogen, oxygen, and carbonic acid gas. All of these may not be given off during a single eruption, or from a single volcano. Some of them may not exist as such in the magmas, because certain chemical combinations may take place immediately after

vapors and gases escape into the air before they can be collected and studied.

Lavas. — *Lava streams.* The molten materials which issue from volcanoes and fissures in the earth, as well as the rocks which result from their cooling, are called *lavas*. When they are in a molten condition, such materials are known as *magmas* (Fig. 253). The temperature of magma is very high, commonly ranging from a little over 2000° F. to nearly 4000° F. In a general way, increase in the percentage of oxide of silicon (same in composition as quartz) in the various minerals of the magma increases the

Fig 257

Lava sheets, representing successive lava-flows, exposed by erosion. Near Pahroc Springs, Nevada (Photo by C D. Walcott for U. S. Geological Survey)

temperature necessary to keep the material molten. The molten lavas of Hawaii, being low in the chemical constituents mentioned, show a relatively low temperature, that is at about 2300° F.

During many volcanic eruptions, magma rises in the crater until it pours over the edge, and flows down the side of the mountain in one or more streams, much as would streams of molten iron (Fig. 254). Lava is white-hot when at a high temperature, and in a highly fluid condition, but it soon changes to a dull-red glow after it leaves the vent. As the magma flows down the mountain and gradually cools, it becomes a thicker liquid (that is more viscous), some minerals begin to crystallize in it, and

finally the whole mass becomes solid lava. A thick lava-flow requires months or even years to become thoroughly cooled (Fig. 255). Lava streams are very commonly from one-fourth to one-half of a mile wide, and from 25 to 100 feet or more deep.

Streams of lava do not always pour out of summit craters of volcanoes. They may break out of the sides of the cones, as has invariably happened in the case of the great active volcano of Mauna Loa, Hawaii, during the last 125 years. In such cases the pressure necessary to lift the columns of molten lava to the summits of the mountains is so great that relief of the pressure takes place by development of one or more fissures on the flanks of the cones out of which the molten lavas pour

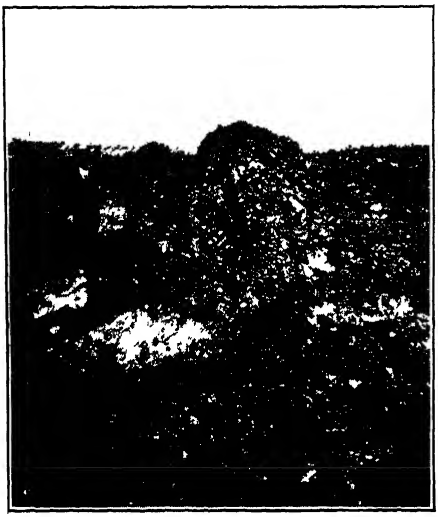

Fig. 258
A spatter-cone on the roof of a lava tunnel. Kilauea, Hawaii. (Photo by the author.)

During the process of flowage and cooling of a lava stream, a time comes when there is a strong tendency for a hard, relatively cold crust to form over the still molten material underneath. It is often possible to walk in comparative safety over such crusts. Molten material of a lava stream may, under favorable conditions, drain away under its hardened crust, leaving a long, narrow, more or less winding cave, or so-called *lava tunnel*. Such tunnels, which usually range in length from a few hundred feet to several miles, and in diameter from 20 to 50 feet, are often remarkably smooth and regular inside (Fig. 259). Under other conditions, the irregular movement of the lava stream may cause its crust to be broken to pieces, and no tunnel results.

A stream of lava in a very hot, highly fluid condition usually flows down a fairly steep mountainside at the rate of from a few

miles per hour to perhaps 8 or 10 miles per hour. As it cools, however, the magma becomes thicker and more viscous, and its rate of motion slowly diminishes until it finally stops. It is not uncommon for streams of lava in Hawaii to continue a slow movement for weeks, or even months.

The distance which a lava stream flows is determined by several factors such as temperature, degree of fluidity, kind of molten rock and steepness of slope. Lavas like those of Hawaii and Iceland are of such a nature that they remain fluid at exceptionally low temperatures for so long that they have commonly flowed for 10 to 25 miles, and, in some cases, even 30 to 50 miles. Extreme cases to the contrary are where lavas are so viscous that they pile up close around the vents as shown by certain recently extinct volcanoes of France and Germany.

Fig. 259
Detail view in a lava tunnel 40 feet high. Gular, Washington. (Courtesy of the U. S. Forest Service.)

Kinds of lavas. When lavas solidify from a molten condition they have either a glassy, or a stony, appearance. Volcanic glass (Fig. 30) (called *obsidian*) is much less common than stony lava. It results from very rapid cooling, especially of the more viscous magmas rich in oxide of silicon. Such a condition is unfavorable for the molecules to build themselves together in the form of crystals, which latter would give the rock a grained, or stony, appearance. Volcanic glass is, among many other places, finely exhibited in Obsidian Cliff in Yellowstone Park, and near Mono Lake, California.

Stony lavas constitute the great bulk of rocks which form from magmas at, and very near, the earth's surface. For their

development, the magma must be sufficiently fluid, and time enough must be given during the cooling, for crystals (usually small ones) to form. The lava may be wholly crystalline, or crystals may be distributed through a glassy groundmass. The mineral composition of some of the most common kinds of lavas — *basalt, andesite, trachyte,* and *rhyolite* — and their relations to other common types of igneous rocks have already been considered (p. 50).

If, during the cooling of a surface magma, some minerals form well-defined crystals scattered through the mass, and then the remaining material solidifies with little or no crystallization, a so-called *porphyritic lava* (Fig. 29) results, that is, one with relatively large mineral grains embedded in a much finer grained, or glassy, groundmass.

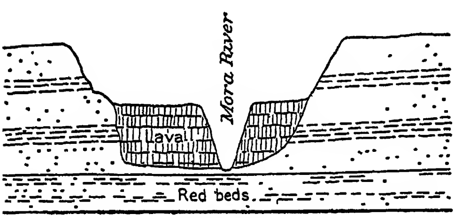

Fig 260
Structure section showing how a lava-flow in a canyon has been trenched by a river. Near Optimo, New Mexico (After U S Geological Survey)

We have already stated that large quantities of gases and steam often escape from lavas for a considerable time after they are poured out of a vent or a fissure in the earth. Such escape of gases and steam through the upper portion of a lava-flow, where the pressure is slight, may fill it with bubbles so that on cooling it becomes *cellular lava* (Fig. 264). If the bubbles are large, giving the rock a spongy appearance, it is called *scoria*. If the bubbles are small, very numerous, and exceedingly thinwalled so that the rock is exceptionally light, sufficiently so at times to float on water, the lava becomes *pumice* which is really igneous-rock froth.

Two Hawaiian terms are commonly used to designate the general character of the surfaces of lava flows. One of these is *pahoehoe* which is applied to generally smooth, though often curved and billowy, surfaces of lava (Fig. 261). The other is *aa* which refers to rough, jagged, badly broken up surfaces, caused either by more or less violent escape of gases or steam, or by the breaking up of a hardened crust by movements of viscous lava underneath it.

Fragmental Products. — These are the materials (usually heated) which are thrown into the air by the explosive action of a volcano, and fall to the ground as solid fragments. They vary in size from the tiniest dust particles to masses of tons weight. The chief sources of such materials are the walls of the throat (or conduit) of the volcano; hardened lava which more or less fills the conduit as a left-over from the preceding eruption; and the upper part of the column of magma which may fill the conduit. Some fragmental products may also be formed by minor explosive action in a stream of molten lava.

Fig. 261

So-called "pahoehoe" lava at the end of a three-mile flow Kilauea, Hawaii (Photo by the author)

Volcanic bombs are pieces of rock, from about an inch to several feet in diameter, which are hurled out of volcanoes. They may be more or less angular blocks torn loose in solid condition, or they may result from violent disruption of molten material whereby masses of the magma, in whirling through the air, take on somewhat rounded forms, and solidify as such. Bombs of the latter sort are often cellular (Fig. 265), or even pumiceous, due to escape of gases.

Fig 262

Part of a field of rough lava. Lassen Volcanic Park, California. (Photo by J. S. Diller, U. S. Geological Survey.)

Volcanic cinders are fragmental materials ranging in size from about an inch down to dust particles. Larger cinders are called *lapilli*, and smaller ones are called *volcanic ashes*. Both types may or may not be porous. The terms " cinders " and " ashes " are good only in the sense that they suggest a resemblance to familiar products of burning, but they are not results of combustion. More or less well-defined beds or layers of the larger fragmental materials (bombs and lapilli), caused by successive eruptions, form *volcanic breccia* which may become consolidated.

Fig 263
A so-called "lava-tree" Island of Hawaii
(Photo by the author.)

Volcanic dust is the most finely divided material ejected from volcanoes. It may be so finely pulverized as to be an impalpable powder which may be sent miles into the air to remain suspended for weeks, or months, and be carried by atmospheric currents for hundreds, or even thousands, of miles. The eruption of dust is an important part of the geological work of volcanoes. Close around the vents of explosive volcanoes, dust not uncommonly accumulates to depths of many feet, and 50 to 100 miles away to depths of several inches (Fig. 266). Successive eruptions often cause volcanic dust and ashes to accumulate in more or less well-defined layers or beds which become compacted into so-called *tuff*.

Character of Eruptions

Effusive Type. — Volcanoes characterized by effusive eruptions are relatively quiet in action, and comparatively free from

severe explosions. Streams of lava either well up in their craters and overflow their rims, or break out of the flanks of the mountains and flow down their sides. The lavas of such eruptions are usually in a highly fluid condition, and flow for miles. Gases and steam of course escape from them in large quantities, but rarely, if ever, with great violence. The two great active volcanoes of Hawaii — Mauna Loa and Kilauea — are excellent examples of the effusive type. They are briefly described beyond in this chapter.

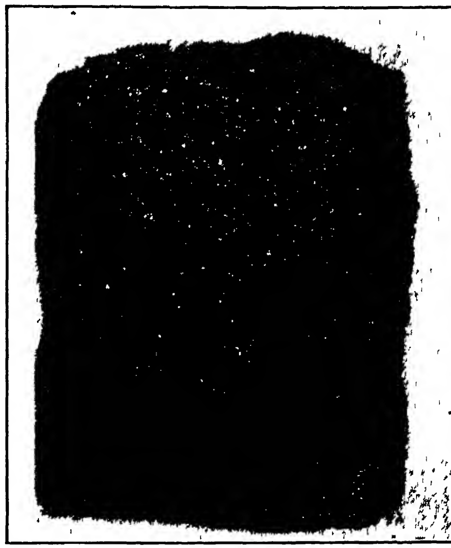

Fig. 264
A specimen of cellular lava. (Photo by the author)

Volcanic cones built up wholly, or largely, by many effusive eruptions are generally characterized by having large craters (or calderas), low angles of slope (usually less than 10°), and great basal diameters. The two last named features are due to the fact that the lava streams tend to flow far out from the vents.

Explosive Type. — Volcanoes characterized by explosive eruptions are violent in action. In extreme cases the top of a cone, or even almost the entire cone, may be blown to pieces and widely scattered. An example of extreme violence was that of Krakatoa in 1883, described beyond. Typical explosive volcanoes seldom yield lava streams, but they commonly send great clouds of volcanic dust and ashes, mingled with steam, high into the air. Large blocks of rock are also often hurled out.

Volcanic cones built up largely by explosive eruptions generally have well-defined craters; their sides are steep (up to 30 or 40 degrees); and the diameters of their bases are relatively small. The two features last mentioned are due to the fact that most of

the materials, in solid form, particularly the coarser fragments, accumulate relatively close around the vents, and produce slopes much steeper than lava-flows. *Cinder cones,* built up by explosive eruptions of volcanic cinders, belong in this category (Fig. 268).

Intermediate Type. — Most of the volcanoes of the world, especially the larger ones, are neither typically effusive nor explosive in action, but rather intermediate between the two. They are characterized by more or less alternation of eruptions of lava streams and fragmental materials. Mt. Shasta, California, and Mt. Rainier, Washington, are the two greatest volcanic cones of the intermediate type in the United States. The active Mt. Vesuvius is another good example. Such cones are usually rather steep-sided, that is their slopes are often 20° to 30°.

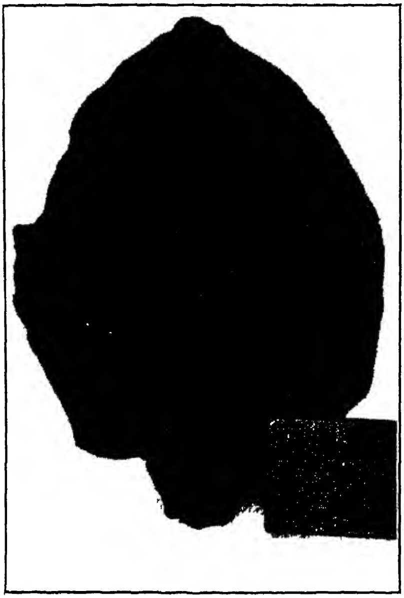

Fig 265
A volcanic bomb from southern Idaho
(Photo by the author)

Fissure Eruptions. — It has already been suggested that not all volcanic materials are erupted from cones. Eruptions may take place through fissures, both small and great, in no way connected with volcanoes in the ordinary sense of that term. The materials thus erupted are always molten rather than fragmental. Some of the best exhibitions of fissure eruptions during the last century and a half have been those of Iceland. Thus in 1783 molten lava poured forth from many places out of a fissure 20 miles long. One of the streams of lava was nearly 50 miles long, and another nearly 30 miles long. Each was several miles wide. As late as 1913, molten lava welled out of a number of very small craters arranged along a fissure, and spread out over the plains.

Fissure eruptions have, in past ages, produced vast fields of lava of great depths. Thus the great lava plateau, covering over 200,000 square miles in Washington, Oregon, Idaho, and northeastern California, has been built up of successive flows, mainly from fissures, to a depth of from hundreds, to several thousand, feet. Valleys were filled, hills were buried, and some mountains were surrounded by the molten floods. These eruptions began in the earlier part of the present (Cenozoic) era, and continued with diminishing force almost to the present time. The great Deccan lava-plateau of western India is even a grander result of fissure eruptions of the present geologic era. Several hundred thousand square miles of lava sheets have there piled up to a maximum depth of over 6000 feet.

Fig 266

Map showing the distribution (depth in inches) of dust from the explosion of Katmai Volcano, Alaska, in 1912 (Drawn by the author, data from National Geographic Society)

Age and Destruction of Volcanoes

New Volcanoes. — A considerable number of relatively small volcanic cones are known to have been built up during the Christian era. Some of these have developed on land, and some in the sea, forming islands. A few examples will be given.

Monte Nuova, a cone 440 feet high near Pozzuoli, Italy, was built up in 1538. A vent was formed by bending up and breaking the ground. Glowing lava was visible, and eruptions of fragmental materials continued for about a week, building up the cone. There have been no eruptions since. The cone stands among others which are not much older.

A remarkable case is that of Jorullo, Mexico, where a volcano burst forth in cultivated fields one day in 1759. Eruptions continued for several years. Large quantities of both molten and fragmental materials were ejected, building up a cone to a height of several thousand feet. A little later (in 1770), activity started at Izalco in San Salvador. Eruptions, often violent, have been almost continuous since that time, and a cone over a mile high has been formed.

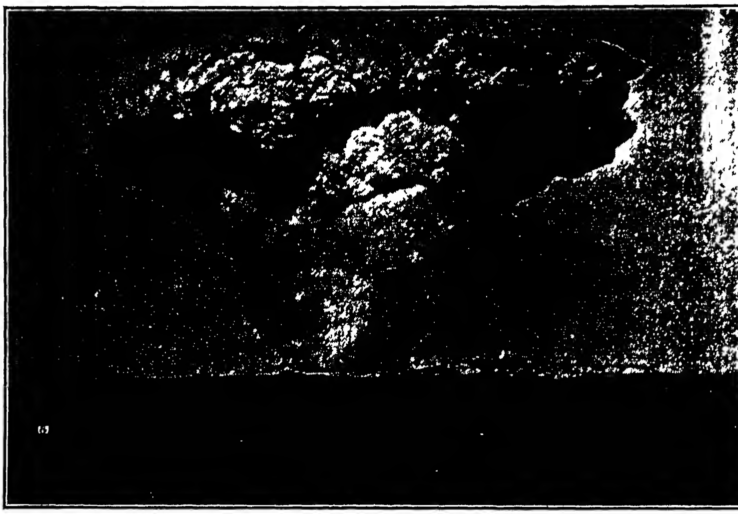

Fig. 267

The grand eruption of Lassen Peak, California, May 22, 1915. The volcanic cloud is fully 8 miles high Photo taken at Anderson, 50 miles away. (Photo by courtesy of Myers and Loomis)

Cinder Cone (640 feet high), and its associated lava field of several square miles, came into existence in northeastern California as a result of eruptions which began not longer ago than the early part of the 18th century. The second and last lava-flow, which poured out during the first half of the 19th century, is probably the youngest lava in the United States.

In 1831 vigorous volcanic activity on the floor of the Mediterranean Sea caused an island of fragmental material 200 feet high to be formed. In a relatively short time it was cut away by wave erosion.

In the Santorin Islands of the Greek Archipelago, several small islands have been formed by volcanic activity during the last 2000 years.

A number of spectacular eruptions in the Aleutian Islands of Alaska, particularly in 1796, 1883, and 1906, have resulted in the formation of islands in the sea.

Various cinder cones in Arizona (Fig. 268) and eastern California are so fresh and unaffected by erosion that they certainly cannot be more than a few hundred, or at most a few thousand, years old.

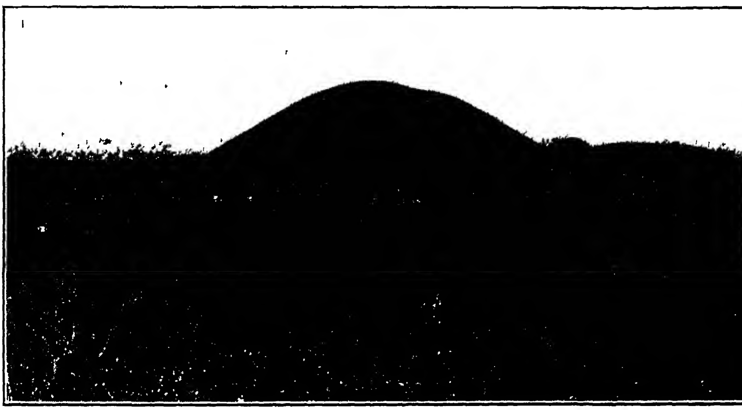

Fig. 268

Group of recent cinder cones San Francisco Plateau, Arizona. (Photo by Gilbert, U S. Geological Survey)

Duration of Volcanic Activity. — Volcanoes have sometimes been classified as active, extinct, and dormant. Such a classification is, however, not very satisfactory because, as has so often happened, a volcano which has been inactive for many years may again break forth. Mt. Vesuvius in Italy, and Lassen Peak in California, are among many examples.

The length of time during which individual volcanoes remain more or less active is exceedingly variable, ranging from a few days (or less) to hundreds of thousands, or even millions, of years. Most of the great volcanoes of the present time began their activity in the early part of the present (Cenozoic) era. They are, therefore, several million years old. Some of them, like Kilauea, are now constantly active; some, like Mauna Loa and

Mt. Etna, are very active at intervals of a few years; others, like Mt. Shasta and Mt. Rainier, are either dormant or practically extinct; while still others, like Mt. Crandall in Yellowstone Park, ceased action so many hundreds of thousands of years ago that the great cones, many miles in diameter, have been very largely removed by erosion. We may gain some conception of the age of big individual volcanoes when we realize that a cone like Mt. Etna has, in spite of many great eruptions, remained practically unchanged in its general outline for more than 2000 years.

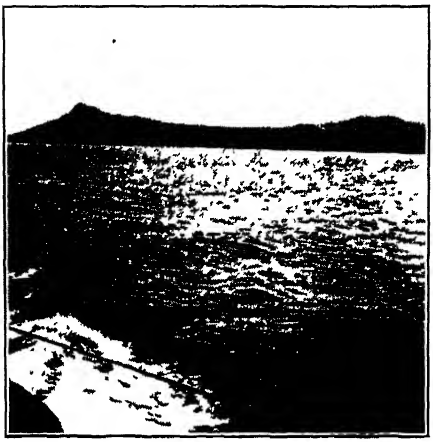

Fig 269

A considerably eroded, extinct volcano Diamond Head, near Honolulu, Hawaii (Photo by the author)

The evidence is plain, from the study of historical geology, that volcanic activity took place during the earliest known (Archeozoic) era of earth history, and that such activity has occurred on small and grand scales in many parts of the world, and during various periods since the earliest known time.

Destruction of Volcanoes. — In some cases volcanic cones are partly, or almost wholly, destroyed through their own explosive activity. Thus an explosion of terrific violence in Katmai Volcano, Alaska, in 1912 blew away several cubic miles of the top of the mountain (Fig. 275), and the explosion of Krakatoa in the East Indies in 1883 almost completely obliterated what was a fair-sized cone. A cone may be partially destroyed by engulfment or subsidence of its upper portion due to weakening of the support underneath. The great crater (or caldera) of Mt. Mazama, containing Crater Lake, in southern Oregon was thus formed (Fig. 322).

The destructive work of weathering and erosion is, however, the greatest cause of obliteration of volcanic cones. Every volcanic cone, even when in course of construction, is subjected to

Fig. 270

A considerably eroded, recently extinct volcano. Mt Shasta, California. (Photo by courtesy of the Southern Pacific Lines)

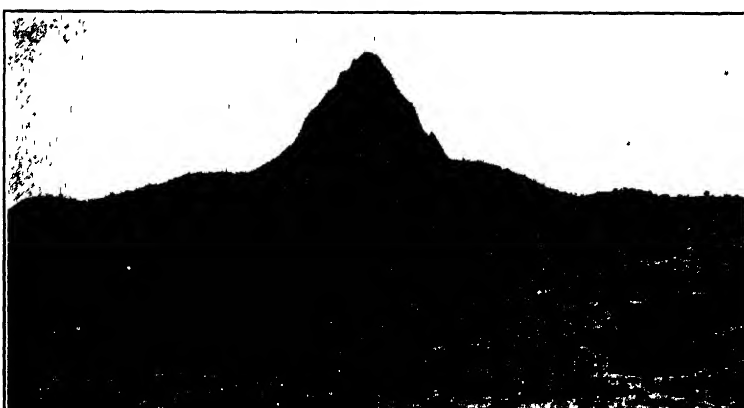

Fig 271

A volcanic neck. Mt. Taylor region, New Mexico. (After Dutton, U S. Geological Survey.)

the attacks of weathering and erosion. The upper part of the cone of Mt. Vesuvius was, for example, distinctly trenched by erosion soon after the great eruption of fragmental materials over its sides in 1906. When, barring very violent eruptions, the amount of material ejected by a volcano is greater than can be removed by erosion, the cone continues to build up. The activity diminishes and finally ceases, after which the cone becomes more and

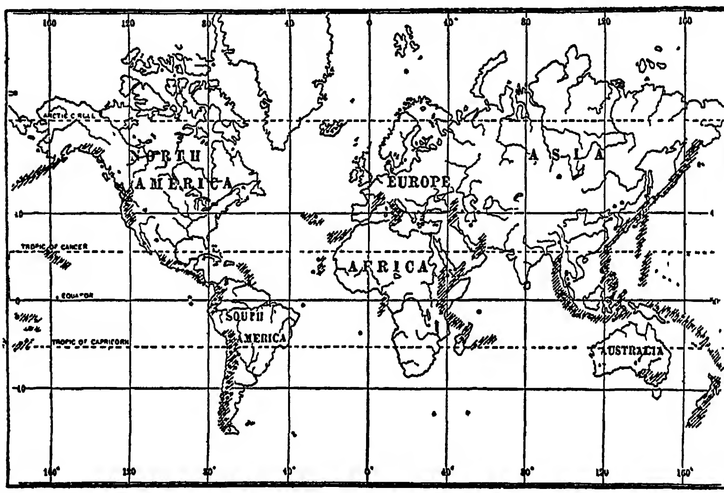

Fig 272

Map showing the distribution of active and recently extinct volcanoes. (From Tarr's New Physical Geography, by permission of the Macmillan Company.)

more deeply dissected (Figs. 269 and 270), its crater becomes obscured, and its height gradually becomes lower. During a late stage of its erosion, nothing but the core or plug of the volcano may rise above the general level of the country (Fig. 271), and finally it may completely vanish as a topographic feature. If, however, the more or less dissected cone should become buried in the earth under accumulations of sedimentary rocks, it might, at a much later time, again become exposed at the surface. An interesting case in point is a very ancient volcanic landscape which is now again coming to light as erosion proceeds in a part of Great Britain.

Rebuilt Volcanic Cones. — When a cone is subjected to a great catastrophe such as a violent explosion, or a profound subsidence of its upper part, a crater pit (or caldera) of large size usually results. In the case of Katmai Volcano, already mentioned, the explosions of 1912 left a hole several miles in diameter, and several thousand feet deep. The cone has not even been partially rebuilt since the catastrophe, though it may be in the course of time.

The vast caldera, over five miles wide and several thousand feet deep, which resulted from the subsidence of the upper part of the cone of Mt. Mazama in Oregon some thousands of years ago, has been only very slightly rebuilt by volcanic activity. Wizard Island (Fig. 322) is a product of such subsequent activity.

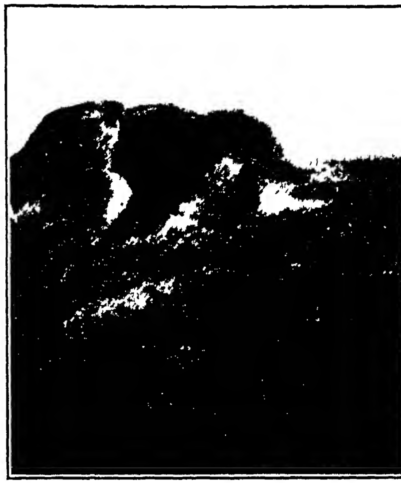

Fig 273
A small vent on the floor of Kilauea, Hawaii. Molten lava issued from this vent for several weeks in 1921 Red hot when the picture was taken (Photo by the author.)

A large portion of Mt Vesuvius was blown away during the great eruption of 79 A.D. Eruptions since then have built the present cone upon the stump of the old mountain.

Submarine Volcanoes

It has already been suggested that volcanic activity may take place on the floor of the sea. A remarkable example is Mauna Loa, Hawaii, which began action at the bottom of the mid-Pacific Ocean where the water was fully three miles deep. It has been built up into a gigantic, gently sloping cone nearly 14,000 feet above sea level. All of the eight Hawaiian Islands mark the highest portions of a great submarine volcanic ridge or range several hundred miles long.

A remarkable case of a great mountain range being built up out of the sea is the chain of Aleutian Islands, Alaska, more than a thousand miles long. It contains various active volcanoes — three new ones (the Bogoslov volcanoes) having been built up as islands in the years 1796, 1883, and 1906

The eastern portion of the West Indies is of very recent submarine volcanic origin, with certain volcanoes, like Mont Pelée and La Soufrière, still active. The East Indies are also to a considerable extent of volcanic origin, with numerous active cones.

Fig 274
Katmai Volcano, Alaska, as it appeared after the great eruption of 1912 (Photo by Griggs for the National Geographic Society)

Among many other examples of volcanoes of submarine origin, mention may be made of the Azores, Cape Verde Islands, Canary Islands, and various islands of the south Pacific Ocean. Mention has already been made of the cone (Graham's Island) which was built up by eruptions in the midst of the Mediterranean Sea in 1831.

Distribution of Active and Recently Active Volcanoes

Hundreds of volcanoes are definitely known to be active, and several thousand others are either dormant, or have become extinct in very recent geologic time, that is during the latter portion of the present era. Most of these volcanoes show a strong tendency toward arrangement into two grand zones or belts (Fig. 272). One of these belts nearly encircles the Pacific Ocean, extending through western South America, Central America, western North America, the Aleutian Islands, Kamchatka, Japan, the Philippine Islands, the East Indies, the New Hebrides, and New Zealand. There are of course various local portions of this belt without volcanoes. The other great belt is less well-defined and more interrupted. Beginning, let us say, in Central America, it extends through the eastern part of the West Indies, the Azores,

the Canary Islands, the Mediterranean region, Asia Minor, southern Arabia and eastern Africa, eastern India, the East Indies, and the Hawaiian Islands. A considerable number of volcanoes lie outside of the two grand belts.

Various ideas have been expressed in the attempt to explain the distribution of most of the active and recently active volcanoes in the two great belts. Without entering into this discussion, suffice it to say that these volcanoes occur in zones where earth-crust disturbances have been recently, and are now, unusually pronounced. They are, in other words, in zones of exceptionally active mountain-building movements. These zones are, in a general way, also the belts of greatest earthquake activity, and,

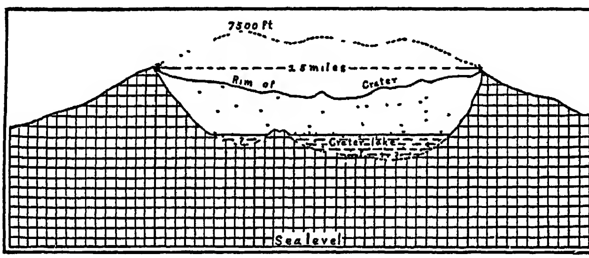

Fig. 275

Diagrammatic section showing the condition of Katmai Volcano, Alaska, before and after the great eruption of 1912. (Drawn by the author, data from National Geographic Society)

as already stated, both earthquakes and volcanoes are but surface and near-surface, manifestations of deeper-seated and more profound earth-crust activity.

Some Great Volcanic Eruptions

A few examples of great volcanic eruptions will now be described briefly in order to give the reader a still more definite conception of the degrees of violence of eruptions, from relatively quiet to highly explosive; of the types of eruptions; the kinds and quantities of materials erupted; the tremendous power involved; and the manner in which volcanic cones may be altered by eruptions.

Mauna Loa and Kilauea. — Two of the most interesting, readily accessible, great volcanoes are Mauna Loa and Kilauea on the island of Hawaii

in the midst of the northern Pacific Ocean They are fine illustrations of the effusive, or relatively quiet, type of volcano Mauna Loa is an exceedingly large volcanic pile with very gently sloping sides rising to nearly 14,000 feet above the sea, and Kilauea lies on its flank at an altitude of about 4000 feet. Each has a vast, oval-shaped crater nearly three miles long bounded by nearly vertical walls of lava many hundreds of feet high. Each crater pit has a nearly level floor consisting of hard, fresh, black lava which is really only a crust covering a mighty column of molten lava, several miles in diameter, extending far down into the mountain Prior to an eruption, the lava column in Mauna Loa rises hundreds of feet in the crater, but, during the last century at least, it has not overflowed the rim Instead, at intervals of about 5 to 12 years, the lava breaks out of the mountainside in the form of a molten stream, somewhere within a few thousand feet of the summit of the cone The resulting relief of pressure causes the column of lava in the crater pit to subside slowly Many such streams of molten lava, from one-fourth of a mile to a mile wide, have flowed down the sides of the mountain 10 to 45 miles, sometimes even into the sea. The great lava stream of 1919 entered the sea, and poured into it for weeks, after flowing about 15 miles from the source on the flank of the mountain Between eruptions, Mauna Loa shows no signs of real activity.

Fig 276

The great spine at the summit of Mt Pelée in the West Indies in 1902 The steaming hot spine was about 1000 feet high (Photo by E O. Hovey, courtesy of the American Museum of Natural History)

Kilauea acts in general much like Mauna Loa. Lava streams have poured out of its flanks also at various times, in each case preceded by a rise of the lava column in the vast crater pit. Within the mighty crater bowl of Kilauea there is, however, an inner pit or crater, about one-third of a mile in diameter, marking a place where the crust of the great column of molten lava in the throat of Kilauea is always broken through, revealing the magma (Fig 253). Within this nearly circular inner pit, with its vertical walls, the

molten lava rises and sinks hundreds of feet within periods of a few years Sometimes the magma overflows the pit and streams out upon the wide floor or Kilauea (Fig. 255). It is, indeed, an awe-inspiring sight to look into the inner pit of Kilauea, especially at night "The boiling lava is apparently white-hot at a depth of but a few inches below the surface, and, in the overturnings of the mass, these hotter portions are brought to the surface and appear as white streaks marking the redder surface portions. From time to time the surface freezes over, and the cracks open and erupt at favored points along the fissures, sending up jets and fountains of lava, the material of which falls in pasty fragments" (W H. Hobbs)

Krakatoa. — Three examples — Krakatoa, Katmai, and Pelée — will be described to illustrate highly explosive volcanic activity Among these, Krakatoa, a volcanic island between Sumatra and Java, had been dormant for over 200 years Then, in August, 1883, a series of terrific explosions lasting two days caused more than a cubic mile of rock material to be thrown into the air in the form of volcanic pumice, ashes, and dust The site of the island was mainly covered with water 600 to 900 feet deep immediately after the catastrophe. Some of the most violent explosions were heard hundreds of miles away. The atmosphere of the whole world was disturbed, as recorded by rise and fall of barometers Part of the vast cloud of dust rose fully seventeen miles into the air. Dust fell in perceptible amounts over an area of several hundred thousand square miles. Small quantities of the finest material filled the whole earth's atmosphere, remaining suspended for months and causing the famous red sunsets of the fall and winter of 1883–1884 Sea waves 75 to 100 feet high, caused by the disturbance, rushed upon the neighboring coasts of Java and Sumatra and killed 40,000 people

Fig 277

A great volcanic cloud which has been called "Vulcan Face" Lassen Peak, California. (Photo by B F. Loomis.)

Katmai Volcano. — Within two days in June, 1912, Katmai Volcano in southern Alaska was subjected to several terrific explosions which were probably of even greater violence than those of Krakatoa The cone, which rose over a mile above the surrounding country, had its whole upper portion, involving about 5 cubic miles of rock, blown away, leaving a vast crater (or caldera) two and one-half miles in diameter and several thousand feet deep (Fig 275). This crater is now one of the world's largest. The first and greatest of the three explosions was heard in Juneau, Alaska, 750 miles away. The product of the explosions was mainly dust which fell to a depth of one foot in a

village 100 miles away (Fig 266), and in perceptible amounts 900 miles away in southeastern Alaska Dust and larger fragments fell to depths of from 2 to 10 feet on the flanks of the beheaded mountain. Glaciers on the mountain were truncated, leaving walls of ice over two miles long capping part of the crater rim Severe earthquakes accompanied the explosions

Mont Pelée. — Mont Pelée, situated on the island of Martinique in the eastern part of the West Indies, was violently active in May, 1902 The last eruption prior to that was in 1851. For a few weeks before May 8, 1902, there was considerable activity accompanied by earthquakes, but on that date a great explosion caused a tremendous cloud of hot gases filled with incandescent particles of dust to rise out of the crater. Because of its weight, this vast cloud rushed with hurricane velocity down the side of the mountain. The city of St Pierre lay in the path of the descending, fiery cloud, and its whole population of nearly 30,000 people (excepting one or two persons) was almost instantly annihilated. Fire finished the work of destruction. A number of violent eruptions took place within the next few months. In October, a remarkable feature began to develop in the crater at the summit of the mountain This was a great column of steaming-hot, more or less pasty lava which slowly rose and solidified, reaching a height of about 1000 feet in seven months (Fig 276) It gradually crumbled to pieces

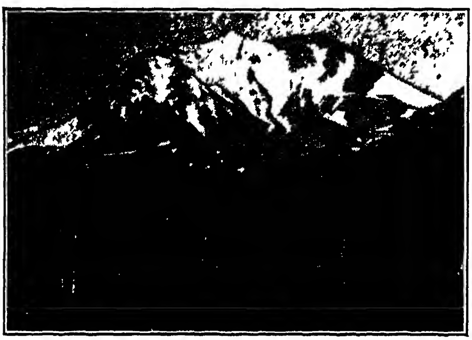

Fig 278

A midsummer view of Lassen Peak, California, from the east, before the eruptions began in 1914 (Photo by B F. Loomis)

Mt. Vesuvius. — Excellent examples of volcanoes of the intermediate type are Vesuvius and Etna For centuries prior to the Christian era, Mt Vesuvius seems to have been inactive. From 63 to 79 A D , numerous earthquakes shook the mountain and vicinity Then, in the year 79, there occurred the most violent eruption of the mountain in historic times No molten lava appeared, but the explosion blew away much of the upper part of the cone, greatly altering its outline, and leaving a conspicuous crescent-shaped ridge around part of the stump of the mountain. "Ashes fell upon the surrounding country, a huge column of steam and ash darkened the sky, and great torrents of water fell upon the flanks of the mountain Pompeii was buried beneath a cover of ash and dust which penetrated every crevice, and so sealed the objects in a compact cover In the excavations which have been made during the last century, objects of even a perishable nature have been recovered. . . . It is a wonderful experience to walk through the deserted streets of this ancient city of 20,000 inhabitants, to realize under what terrible conditions the people were driven out or overwhelmed in their efforts to escape" (Tarr

and Martin) The city of Herculaneum was, at the same time, overwhelmed by a great flow of hot mud, formed by clouds of condensing steam mixed with ashes Between 79 A D and 1139, a number of eruptions occurred Then for nearly 500 years there was scarcely any activity. One of the greatest eruptions of Vesuvius occurred in 1631 when large quantities of ashes and dust were ejected, and several streams of molten lava poured out of the crater and down the sides of the mountain, overwhelming some villages. Since that time activity varying from mild to vigorous has been almost continuous, and the present cone (altitude nearly 4000 feet) has been built upon the stump of the mountain left by the explosion of the year 79 A grand eruption took place in 1872 when vast clouds of ashes and dust were thrown high into the air, and streams of lava flowed out of fissures in the sides of the cone. The latest eruption, nearly as great as that of 1872, took place in 1906 when ashes and dust were thrown miles into the air, and several streams of lava flowed out of breaches in the mountainside.

Fig. 279

Lassen Peak as it appeared from the east after the devastating eruption of 1915. Compare with Fig 278 (Photo by A. L. Day, Carnegie Institution of Washington)

Mt. Etna. — The cone of Mt Etna in Sicily rises to a height of nearly 11,000 feet Its base is over twenty-five miles in diameter. Many vigorous eruptions have taken place since the first known one in 476 B C. During the last 100 years, eruptions have occurred at average intervals of about 5 years. Destructive earthquakes usually precede and accompany the violent eruptions A typical eruption is characterized by a series of explosions which send vast clouds of ashes and steam into the air from the great summit crater, while, from several (or many) openings on the flanks of the mountain, there issue, streams of molten lava, some of which flow down to the base of the great cone, and even into the sea. The openings from which the lava streams emerge are secondary craters, often in small cones, hundreds of which occur on the sides of Etna. Grand eruptions took place in 1910–1911 when many vents on the sides of the mountain poured forth lava, and the summit crater ejected dust and ashes. The latest great eruption took place in 1923.

Lassen Peak, California. — In conclusion, brief mention may be made of Lassen Peak in northern California which is of special interest not because of the magnitude of eruptions, but because it is the only active volcano in the United States proper. The steep-sided cone of Lassen rises about a mile above the surrounding country (Fig. 278). Prior to May 30, 1914, the mountain

had been inactive for hundreds, or even thousands of years, as judged by the state of weathering of its crater. On the date mentioned, the old volcano suddenly burst into explosive activity, and hundreds of eruptions occurred within the next few years Little or no lava appeared, but great clouds of steam and dust were shot into the air, often to heights of several miles (Figs 267 and 277), and scattered ten to thirty miles around the mountain. During a grand eruption of 1915, a tremendous volume of condensing steam mingled with volcanic dust started down the eastern face of the cone, causing the snow to melt The resulting flood of hot mud and loose rock fragments, together with the very hot volcanic cloud, rushed with terrific speed to the base of the cone, and into a beautiful mountain valley, leaving an appalling scene of desolation for ten miles. Forests were swept away for miles, and fires were set (Fig. 279) Eruptions have been rare during the last few years, one having been reported in October, 1920, and another in December 1923.

Cause of Volcanic Activity [1]

The problem of the cause (or causes) of volcanic activity is one of the most uncertain in geological science. Our present purposes are to call attention very briefly to some of the more important facts involved, and to offer a few explanatory suggestions.

A long-held idea that a relatively thin crust covers a molten earth-interior, and that downward pressure of this crust, due to earth contraction, causes molten rocks to be forced out, has been too thoroughly disproved to be now seriously entertained The fact that near by volcanoes, like Mauna Loa and Kilauea, commonly erupt entirely independently, shows that there can be no universal liquid beneath a relatively thin crust Other arguments against liquidity of the earth's interior are that the earth acts like a body nearly as rigid as steel against the powerful tide-producing forces, and that earthquake waves, which pass through the earth to a depth of at least 2000 miles, are of the kind which require a solid medium for transmission.

We may, then, consider more plausible views in regard to the cause of vulcanism First of all, we may be sure that the earth is highly heated inside Measurements made in deep borings show that the temperature increases downward at the rate of about 1° F for each fifty to seventy-five feet to depths at least somewhat greater than a mile The temperature must, therefore, be several thousand degrees at depths of twenty-five to forty miles. This is sufficiently high to cause all ordinary rocks to melt at the earth's surface. At great depths, however, the downward pressure on the rocks is so tremendous that their melting points are notably raised, so that there is every reason to believe that the rocks twenty-five to forty miles down are in general not molten.

If we adhere to the older (nebular) hypothesis of earth origin, the interior heat of our planet is left over from its once molten condition On the basis of another (planetesimal) hypothesis, the earth's heat is maintained by the

[1] This statement of the cause of volcanic activity is taken essentially from the author's volume 3 of Popular Science Library published by P. F. Collier and Son Company.

steady, powerful action of gravity, which causes the earth to contract. The earth is, in any case, hot inside as proved by deep-well records and by igneous phenomena in general, and it is a shrinking body as proved by the many large-scale zones of wrinkling and folding of the rocks If, then, highly heated, solid rocks at reasonable distances down in any part of the earth are subjected to relief of pressure by an earth movement, such as upward crumpling or bending of the crust, or by readjustment of large fault blocks, such heated, solid rocks would become locally molten. The same crustal disturbance which brings about such relief of pressure and melting may very reasonably be regarded as the power which forces some of the newly formed molten material higher up into the crust, and even out upon its surface This view harmonizes with the well-known fact, already mentioned, that the main belts of active volcanoes are also the main belts of active earth movements, such as earthquakes.

Another source of power behind volcanic action is steam and gas pressure. We have already referred to the fact that tremendous amounts of water, in the form of steam, escape from volcanoes, and even from streams of molten lava The violent volcanic explosions are all, or nearly all, direct results of giving way of volcanic cones to steam (and gas) pressure which increases during greater or less periods of time, and with little or no possibility of escape without rupturing the mountain Steam alone, or combined with some other gases, may also aid in forcing out the molten rock.

What is the source of the steam and other gases or vapors? According to one view, they were originally within the earth According to another view, the water, at least, has been absorbed by the molten rocks from surface waters which have worked their way downward into the earth's crust. At least three arguments are opposed to the second hypothesis first, that a considerable number of volcanoes are many miles from the sea or other large bodies of water; second, that downward percolation of rain water would fall far short of supplying the tremendous quantities of water ejected by volcanoes; and third, that any water taken up by molten rock must be absorbed within a very few miles of the surface because farther down (in the zone of flow) there are no openings large enough to permit any very notable downward passage of water As a matter of fact, the uppermost portion of the earth's crust is just where magmas give up their water, often with great violence.

CHAPTER XII

SUBSURFACE WATER

Sources, Amount, and Disposal of Subsurface Water

All water which occurs below the surface of the earth may be called *subsurface water,* or *underground water,* or simply *ground water.* There is good reason to believe that water (or at least its component parts) occurs intimately associated with the rocks deep down within the earth, that is well below the zone of fracture This is strongly suggested by the large quantities of steam given off through volcanoes and from magmas which are poured out on the earth's surface. Our present concern is not with any such very deep-seated water, but rather with ground water which occurs in the zone of fracture, that is within the outer, crustal portion of the earth.

The source of all but a very small quantity (probably not over one per cent) of subsurface water in the zone of fracture is atmospheric precipitation, that is rainfall and snowfall. It has been estimated that about 1500 cubic miles of water (including its frozen state — snow) falls upon the surface of the United States yearly. One-half, or somewhat more, of this evaporates; about one-fourth of it flows off in surface streams; and the remaining one-fourth, or somewhat less, works its way into the crust of the earth either by soaking into the loose materials, or by entering cracks, fissures, and other openings in the bed rock. Some of the factors which favor descent of water into the earth's crust are humid climate; dense vegetation which interferes with run-off (surface flow); gentle slopes which retard run-off; and a relatively high degree of porosity and fissuring of the rock materials.

Some conception of the quantity of ground water may be gained from the statement, based upon a careful estimate, that all of the water in the soils and rocks of the first 100 feet below the surface of the United States would be sufficient to form a surface layer 17 feet thick. In the sections of the country with humid climate, the amount of water in the first 100 feet would of course

be greater than the average. It should not be assumed, however, that anything like such a proportionate amount of water in rocks continues to depths of miles, or even of thousands of feet. The absolute limit of depth beyond which any very appreciable amount of ground water, in the ordinary sense of that term, can exist is only about 8 to 12 miles, depending upon the hardness of the rocks. This is because the tremendous pressure of the overlying rocks makes it impossible for very appreciable openings to exist beyond such depths. Very little surface water ever reaches such extreme depths. Most of the underground water by far occurs within a few thousand feet of the surface. This conclusion is borne out by the fact that, in deep mines in various parts of the world, little or no water is usually encountered lower down than a few thousand feet. Large fissures containing water are, however, sometimes found in deep mines. Some moisture no doubt is held in the pores of the rocks beyond depths of a mile or more.

What becomes of the water which descends into the earth's crust? A large amount returns to the surface through springs and seepages, a large amount moves to the surface by capillarity in loose rock materials, and then evaporates; plants absorb much water which is drawn up into the leaves to be evaporated; a considerable amount is removed through wells; some travels underground to emerge as springs in the sea relatively near shore, as is known to be the case in the Gulf of Mexico, and in the Mediterranean Sea, some enters into chemical combination with various minerals and rocks to be held there, often for ages of geologic time; and some makes its way so far down in crevices and pores of the rocks that it remains for a very long time.

Modes of Occurrence of Subsurface Water

Water in Loose Rocks and Soils near the Surface. — There are three general modes of occurrence of subsurface water: (1) In loose materials relatively near the surface; (2) in porous consolidated rock layers or formations, usually well below the surface; and (3) in cracks, fissures, and other openings in hard rocks. Loose rock formations and soils are, in most humid regions, saturated with water at greater or less depths (usually less than 75 feet) below the surface. This statement is borne out by the fact that water may be obtained almost universally from wells in

such regions within 25 to 75 feet of the surface. More or less moisture of course occurs in the materials above the zone of saturation. In arid and semi-arid regions there is often no zone of saturation in the loose, incoherent materials just below the surface, or in case it is present, it is usually farther down than in humid regions.

The porosity of many loose soils and rocks is surprisingly high. Thus 25 to 40 per cent of the volume of common sand is pore space, while in loam it is usually 40 to 50 per cent. It is clear, therefore, that one-fourth to one-half of the volume of such material, when saturated, is water.

Water in Porous Rock-layers. — Very considerable amounts of water occur in more or less definite layers or formations which

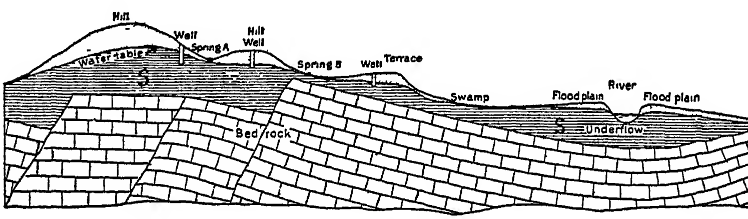

Fig 280

Structure section illustrating various principles of the occurrence of subsurface waters. (After U. S. Geological Survey)

often extend at various angles for hundreds, or even some thousands, of feet into the earth. Such water-bearing layers or formations are known as *aquifers*. An aquifer is usually bounded above and below by material rather impervious to water. An excellent example of an aquifer on a large scale is the Dakota sandstone formation of South Dakota and Nebraska. Almost anywhere across Nebraska, a well drilled through a thick formation of clay, and into the porous Dakota sandstone, strikes water (Fig. 281). In such an aquifer, water travels long distances. Thus water obtained from a well in the Dakota sandstone formation in eastern Nebraska has traveled actually hundreds of miles under the state from the eastern front of the Rocky Mountains where surface water entered the upturned and exposed edge of the porous formation.

Travel of underground water in aquifers for greater or less

distances is common in many parts of the world. Such water does not of course flow freely in distinct underground channels, but rather it moves along slowly, working its way between the grains of the porous rock, and encountering much friction. The rate of motion is much slower than might be supposed. Data from various sources indicate that water in an aquifer of even coarse sandstone travels only about one-fifth of a mile per year. In many aquifers the rate of flow is much less.

Among the consolidated strata, sandstones and certain limestones are usually the most porous, their volumes of pore space often being 20 to 30 per cent.

Water in Cracks and Other Openings in Hard Rocks. — The least amount of subsurface water occurs in the hard, bed rock

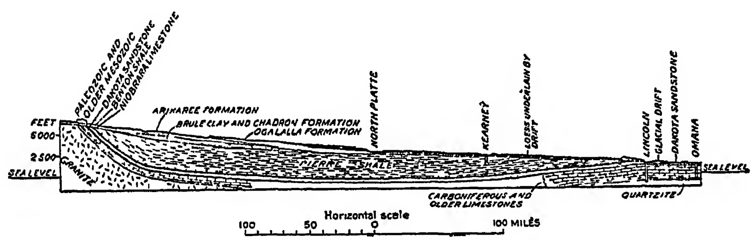

Fig 281

Structure section from the Rocky Mountains to Omaha, Nebraska, showing the position of the Dakota sandstone aquifer (After U S Geological Survey)

formations. With the exception of the small quantity rather firmly fixed in the tiny pores of the rocks, most of such water occurs in joint cracks, fault fractures, or more or less well-defined channels. Many formations, such as granite and other types of crystalline rocks, are neither in definite layers, nor are they porous enough to permit water really to flow through their masses. The porosity of hard, deep-seated igneous and metamorphic rocks is generally less than one per cent.

We have already learned that joint cracks are very common, and usually closely spaced, in all kinds of hard rocks in the outer (zone of fracture) portion of the earth's crust. Such cracks are usually more or less irregular in both direction and spacing. Fault fractures, which are not so abundant, are often rather

regular and straight for considerable distances. As would be expected, the ease with which water may travel along such cracks and fractures varies greatly. Many times the passageways are sufficiently long and open to permit water to follow them readily for hundreds, or even thousands, of feet. In the bottoms of deep canyons, water may emerge from cracks in hard rocks many hundreds of feet below where it entered the earth. It must be evident, from the above statements, not only that subterranean water does not exist in cracks and fissures in hard rocks in great amount, but also that its movements are usually very irregular.

In limestone, even where it is exceptionally dense, and to a less extent in other rocks, underground water often enlarges passageways into more or less distinct channels along which actual underground streams may flow. Such streams may reach the surface in the form of springs. Echo River, which flows through the bottom of Mammoth Cave, Kentucky, is a fine large-scale example (Fig. 295). In a great lava region, such as the island of Hawaii, subsurface water often flows through lava tunnels, the origin of which we have already explained. In view of the facts just stated, it may be readily understood why regions immediately underlain with thick formations of limestones or lava usually have relatively few surface streams, this being because the waters easily find their way into underground channels.

The Water Table. — The surface below which the soils and rocks are saturated with water is called the *water table*. The term does not apply to a saturated layer or formation (*aquifer*) capped by an impervious layer or formation. The water table most typically lies in soil which rests upon bed rock in a humid region. In such a place surface water works downward, filling all cracks and crevices in the bed rock, and saturating the lower portion of the soil, while the upper portion of the soil is only moist. The top of the saturated zone is the water table. It has already been suggested that there is no universal zone of saturation, particularly in arid regions.

The water table is very irregular, but it is generally farther under the surfaces of hills than of valleys. This is because the water at the higher levels tends to migrate, under the action of gravity, to the lower levels. After prolonged rain, the water table may coincide almost, or quite, with the earth's surface over a considerable area, as was the case at the time of the Dayton,

Ohio flood of 1913 when the ground was nearly everywhere thoroughly soaked, causing a maximum run-off. In the soil-covered, humid portions of the United States, the water table ranges very commonly in depth from the surface to 40 or 50 feet. Springs, swamps, ponds, and lakes not infrequently mark places where the surface of the ground either intercepts, coincides with, or passes below the water table (Fig. 280). The water table lowers steadily during long periods of dry weather, and this explains why so many wells, springs, and swamps, which are dependent upon the upper portion of the saturated zone, go dry.

Springs

Ordinary Springs.[1] — The term *spring* is applied to subsurface water which emerges from the ground. Springs may be divided, according to their modes of origin, into gravity and artesian springs, and, according to the nature of the passages traversed by the water, into seepage, tubular, and fissure springs.

A *gravity spring* is one whose water is not confined between impervious beds, but flows from loose materials or open passages under the action of gravity, just as a surface stream flows down its channel (Fig. 282). What may be called an *aquifer spring* is similar to a gravity spring, but its water follows a porous layer confined between impervious beds (Fig. 283).

An *artesian spring* is one whose waters are confined in impervious channels, or (in porous layers) between impervious beds, and are under (hydrostatic) pressure because the water level at their source is higher than the point where they emerge (Fig. 286).

Seepage springs are springs in which the water seeps out of sand or gravel. They may emerge along the top of an underlying impervious bed, but more commonly they occur where valleys are cut downward into the zone of saturation of a more or less uniform water-bearing deposit (Fig. 282). Seepage springs are commonly of the gravity type, but, where the channels or fissures emerge beneath beds of sand or gravel, seepages not infrequently result from true artesian springs.

Tubular springs embrace a great variety of flows, including both those in the small more or less tubular passages in (glacial)

[1] The following statements in regard to ordinary springs are taken largely from U. S. Geological Survey Water-Supply Paper No. 255.

drift, and those occupying large (and small) solution channels or caverns in soluble rocks. The channels of springs in the drift are generally established along some more or less sandy or other porous layer, or perhaps along the path left by a decaying root. In limestones and other soluble rocks, the underground passages

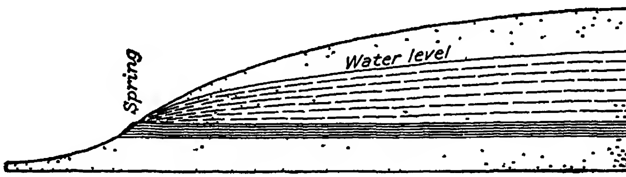

Fig 282
Diagrammatic section illustrating a water-table spring (After U S Geological Survey)

may reach many miles in length. Some of these passages are many feet in diameter, and are traversed by streams of considerable size, or even by rivers (e.g Echo River in Mammoth Cave). Tubular springs are most commonly of the gravity type (Fig. 285), but in some cases the water may be under considerable artesian pressure in the lower parts of its channel, or even at its outlet.

Fissure spring is a term used rather comprehensively to include the springs issuing along bedding, joint, cleavage, or fault

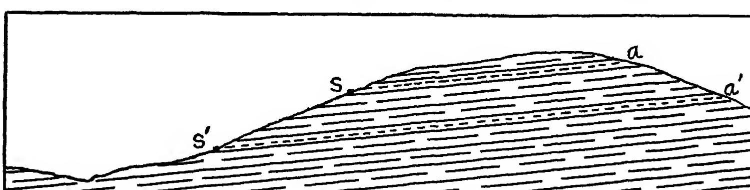

Fig 283
Diagrammatic section illustrating aquifer springs (Drawn by the author.)

surfaces (Fig. 286). The distinguishing feature is a break (or network of breaks) along which the waters can pass, it being immaterial whether any considerable open space exists. Springs of this class are often distributed along straight lines for considerable distances, their position being determined by lines of fracture

which are often faults. Spring water may also emerge after following a very devious course along irregular joint cracks far below the surface.

Hot Springs. — *Hot springs* may be regarded as those whose temperature ranges from that of the human body to the boiling point of water. The two most common causes of the heating of the waters of hot springs are the following. (1) The water may pass through masses of volcanic rocks of recent geologic age which

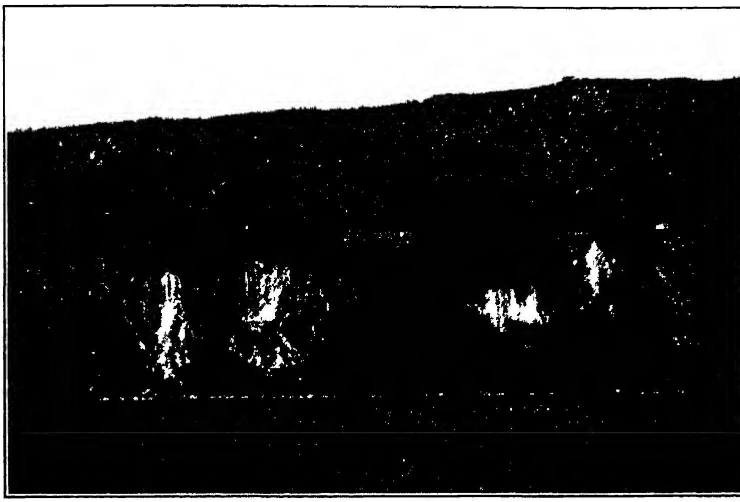

Fig 284

Springs issuing from a bed of gravel between layers of lava. Thousand Springs, Idaho (Courtesy of the U. S. Reclamation Service)

have not yet cooled to the normal temperature of the earth's crust. Yellowstone National Park contains thousands of such hot springs (many of them boiling) where, during the present (Cenozoic) era, successive outpourings of lava covered a wide area many hundreds of feet deep. Fine examples also occur in the Lassen Peak region of northern California, and in many other parts of the world. (2) Water may, where the rock structure is favorable, pass far enough below the surface to have its temperature notably raised by the general heat of the earth's interior, and then rise to the surface under (hydrostatic) pressure. It has

already been stated that the temperature of the earth increases downward at the rate of about 1° F. in 50 to 75 feet. Water emerging from a depth of a few thousand feet would, therefore, be notably warm. Such springs are, however, usually not very

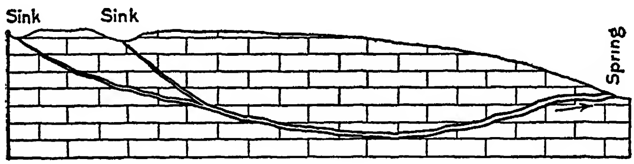

Fig. 285
Diagrammatic section illustrating a tubular spring (After U. S. Geological Survey.).

hot, and rarely, if ever, actually boiling. They emerge usually from prominent fault fractures which extend to great depths, generally where the rocks are also much folded. There are many examples in the southern half of the Appalachian Mountains, as at Hot Springs, Virginia. Among many other examples are Hot Springs, Arkansas; near Ogden, Utah; and in parts of southern California.

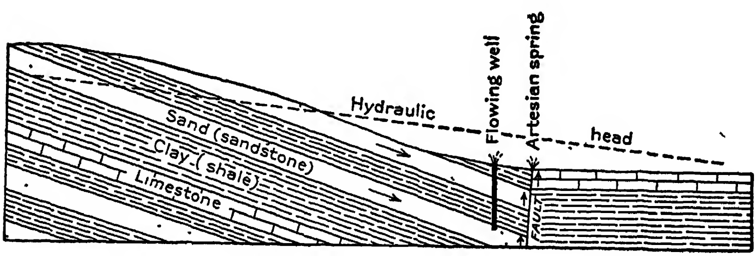

Fig. 286
Diagrammatic section illustrating a fissure (or artesian) spring. (After U S Geological Survey)

Other sources of heat of underground water may be chemical action; friction due to rubbing of rock masses against each other, as during faulting; and possibly radio-activity, but these are probably much less important than the two sources above explained.

Geysers are periodically eruptive hot springs found only in a few of the recent volcanic regions of the world, such as Yellowstone Park, Iceland, and New Zealand. They are exhibited most wonderfully in Yellowstone Park where many of them erupt columns of hot water to heights of 25 to 250 feet at intervals varying from an hour or less to many days (Fig. 287). Old Faithful Geyser erupts once about every 70 minutes, each time sending over a million gallons of hot water, in the form of a column several feet in diameter, to a maximum height of about 150 feet.

Fig 287

A group of hot springs and geysers Yellowstone National Park. (Photo by Hillers, U. S Geological Survey.)

The general explanation of geyser action may be stated briefly as follows: The very irregular geyser tube extends downward nearly vertically into a mass of hot lava. The tube is filled with water from openings in the immediately surrounding rocks. The boiling point of the water toward the bottom of the tube is considerably greater than it is at the surface because of the pressure of the column of water. Finally, however, the hot lava causes the water to boil far down in the tube, in spite of the pressure. The first steam to form causes the whole column of water to lift slightly, thus relieving the pressure on the superheated water far down, and resulting in a quick development of much steam which violently forces most of the water out of the geyser tube.

Mineral Springs. — Water begins to take mineral matter into solution as soon as it enters the earth. Where surface drainage enters the earth, some mineral matter is already in solution. The amount of material dissolved depends upon various conditions such as the distance the water travels, the kind of rock traversed, the pressure, the temperature, and the content of gas In many cases, especially where the water goes but a short distance below the surface in difficultly soluble materials, the amount of mineral matter in solution may be so slight as to be unnoticed by ordinary

Fig. 288

Detail view of a part of Mammoth Hot Springs Yellowstone National Park (Photo by Jackson, U S. Geological Survey)

observation In many other cases, however, particularly where the material is relatively soluble, or where the water travels far down, much material may be taken into solution, causing the water to become more or less highly mineralized. Such water, emerging at the earth's surface, forms a *mineral spring* which may be cold or hot. Mineral springs, and also wells, often yield so-called hard water which contains much calcite, dolomite, gypsum, or certain other mineral salts in solution. Wells and springs in limestone regions characteristically yield hard water. Soft water usually emerges from openings in igneous rocks, such as granite and lava, and from other rocks which contain very little limy

matter. Mineral waters may contain sulphuretted hydrogen, carbonic acid gas, and other gases A carbonated spring is highly charged with carbonic acid gas which escapes from the emerging water on account of the relief of pressure. Mineral springs may be either hot or cold. Mineral waters are often more or less medicinal in their effects.

WELLS

Kinds and Depths of Wells. — Water wells are sunk in various ways, the most common of which will be mentioned. Most wells by far are simply *dug* down in loose materials to a little below the water table. The depth seldom exceeds 50 feet in humid regions. Wells are often *bored* in loose materials with large augers, rotated by a power-developing machine, to depths of 100 feet, or somewhat more. Wells may also be *driven* in loose materials by forcing small metal tubes with perforated points to depths of 50 to 200 feet.

In hard bed-rock formations, wells for water and oil are usually *drilled* by the percussion of a long, heavy steel weight which is raised and suddenly lowered repeatedly from a derrick. Many wells have been drilled to depths of thousands of feet. Among several very deep wells in West Virginia, one showed a temperature of 172° F. at 7000 feet, and little or no water was encountered in it all the way down A well over 7300 feet deep in southeastern Germany showed a temperature of 186° F. at the bottom. In 1929 a well 9280 feet deep was drilled in southern California.

The drilling of deep wells, where samples of the rocks from different levels have been saved, has been an important aid to the geologist in rendering more precise a knowledge of the kinds, thicknesses, and structural relations of the rocks underground.

Artesian Wells. — When a well, sunk to a porous water-bearing layer or formation, or a crack or fissure filled with water, encounters water under enough pressure to cause it to rise more or less in the hole, we have an *artesian well.* The water is often under a tremendous so-called "pressure head," but it may, or may not, flow out upon the earth's surface.

Requisite conditions for the most common type of artesian well are the following: a porous layer between water-tight layers;

exposure of at least an edge of the porous layer so that water may enter it; inclination of the water-bearing layer (aquifer) so that the water will move downward in it under the action of gravity; absence of a ready escape of the water at a lower level than that of the well; and an adequate rainfall to furnish the supply of water.

An aquifer like that just described may extend under a valley, and outcrop on the hills on each side as shown by Figure 289; or

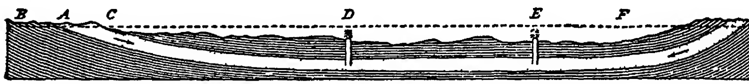

Fig 289

Structure section illustrating flowing wells in a synclinal basin. (After U S Geological Survey)

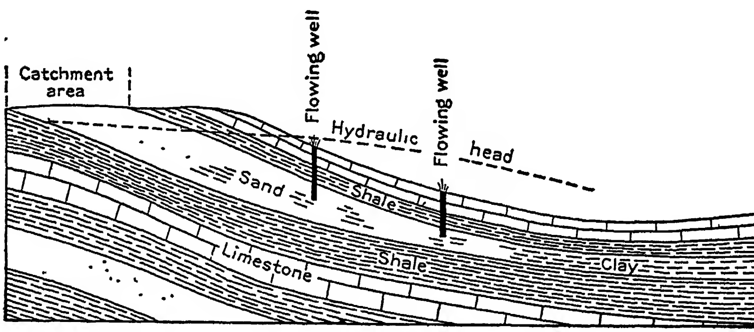

Fig. 290

Structure section illustrating flowing artesian wells in a monocline (After U S Geological Survey)

it may be tilted in one direction and thin out, or grade into impervious material, as shown by Figure 290 In either case a flowing artesian well would be obtained by sinking a well through the upper water-tight layer into the aquifer. Some artesian basins are very extensive (Fig. 281), and the water emerging from a well in such a basin may have traveled hundreds of miles underground.

If an aquifer, lying between water-tight beds, curves downward (synclinally) under a ridge, as shown by Figure 291, a well sunk to the aquifer from high up on the hill would be non-flowing,

although the water might rise under great pressure to a considerable height in the hole. In none of the cases described will the water rise to the level of its source (or intake) because friction during the passage of the water through the porous rock layer reduces notably the pressure, the more so as the distance increases.

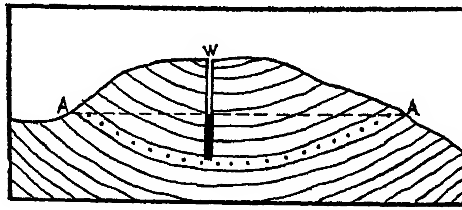

Fig 291

Structure section illustrating a non-flowing well in a synclinal area Dotted formation is the aquifer (Drawn by the author)

Much less commonly than the cases just mentioned, both flowing and non-flowing artesian wells may result where water is encountered under pressure in cracks, fissures, or channels in dense or hard rocks as suggested by Figure 292.

Wells and Sanitation. — Fully two-thirds of the people of the United States depend upon wells for their water supply. Most of the people by far in the upper Mississippi Valley region use well water. The location of wells with reference to sanitary conditions is, therefore, of very great importance. Failure to give

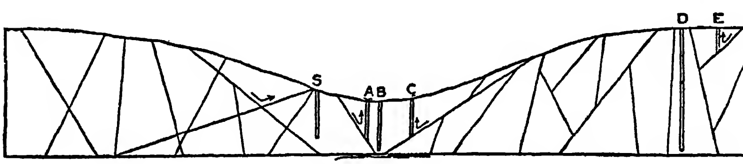

Fig. 292

Diagrammatic section showing springs and flowing wells in jointed rocks. (After U S. Geological Survey.)

reasonable attention to simple, fundamental precautions is a reason for a large amount of sickness which could be avoided, especially in country districts.

Germ-laden water may travel surprisingly far underground. Water contaminated by barnyards, cesspools, and outhouses spreads notably on sinking to the water table in loose materials, often causing water in shallow (dug) wells close to houses and

barns to become more or less germ-laden (Fig. 293). The safe well must be situated out of range of such contamination. Germ-laden surface water may also travel underground through fissures, cracks, or channels in bed rock, and contaminate wells and springs. Less often the surface, and near-surface, drainage may be down a hillside, while contaminated water may flow in the opposite direction underground in a porous layer of tilted bed rock. Even after a well has been carefully located in the light of the principles suggested, sanitary analyses of the water should be made once or twice a year to insure reasonable safety.

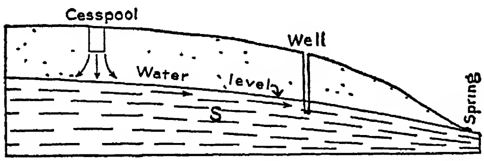

Fig 293

Structure section showing one way by which wells and springs may be polluted (After U S. Geological Survey)

Work of Solution by Subsurface Water

Solvent Action of Subsurface Water. — Mention has already been made of the fact (p 336) that water begins to take more or less mineral matter into solution as soon as it enters the earth. Pure water has some power to dissolve mineral matter, but the carbonic acid gas, and other gases and acids, which it takes up from the air and from the decomposing organic matter in the soil, greatly increase its solvent power. If it moves downward far enough, it also becomes warm (or hot) and gets under pressure, thus making it a more powerful solvent. The most common rock which is readily

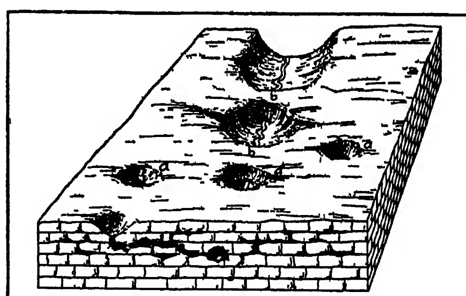

Fig 294

Diagram illustrating the origin of caves (in black), sink holes (a), and natural bridges in limestone (After H. F. Cleland)

soluble in such water is limestone, which consists largely, or wholly, of either calcite or dolomite. Gypsum and salt-bearing strata are readily attacked. Many other minerals, even as resistant as feldspar, also are taken at least partly into solution.

Amount of Material Dissolved. — One of two principal things may happen to mineral matter taken into solution by subsurface water. It is either carried deeper down into the zone of fracture and there deposited in openings in the rocks, or it is brought to the surface, mainly through springs, to be carried to the sea by surface streams. The deposition of materials at lower levels is discussed beyond in this chapter. Even roughly approximate figures in regard to the amount of material deposited at lower levels in the zone of fracture cannot be given, but the quantity is certainly large. In the discussion of the rate of erosion of the United States (p. 154), it is stated that, according to good estimates, the rivers of the country carry about 270,000,000 tons of dissolved mineral matter to the sea each year. Most of this enormous amount of material is taken into solution by underground waters within a few hundred feet of the surface, and fed into the streams through springs. Underground water, therefore, contributes notably to the general process of wearing down (erosion) of the lands, because the surface streams, as they cut down, have less rock material to remove.

Fig 295

Echo River in Mammoth Cave, Kentucky. (Photo by courtesy of the Mammoth Cave Company.)

Caves, Sink Holes, and Natural Bridges Formed by Solution. — An important result of the solvent action of subsurface water, particularly in limestone regions, is the development of *caves* (or *caverns*). One of the most remarkable examples is Mammoth Cave, Kentucky. This wonderful work of nature is entirely the result of the action of underground water which has dissolved (and to some extent corraded) and carried away tremendous quantities

of limestone. There are scores of miles of intricate passageways and galleries, some of them very large. A stream, called Echo River, aided by its tributaries, is still carrying on the work of solution, and so the cave is being enlarged (Fig. 295). Among other famous, large caverns similarly found in limestone are the recently discovered Carlsbad Cave, New Mexico; Oregon Caves, Oregon; Wind Cave, South Dakota; Wyandotte Cave, Indiana; and Luray Cave, Virginia.

Fig 296
A stream entering an underground passage in limestone Nakimu Caves, British Columbia (Photo by the author)

An opening which connects a cave with the surface is called a *sink hole.* Sink holes may be formed either by the solvent action of surface water which finds its way into a cave, or by the collapse of part of the roof of a cave.

A *natural bridge* may be formed by the collapse of all but one portion of the roof of a cave. A famous example is the Natural Bridge of Virginia. Natural bridges are formed also in other ways, one of which is described on page 213.

Deposition by Subsurface Water

Cave Deposits. — When water containing carbonic acid gas passes downward through a limy formation it becomes more or less lime-charged. A drop of such lime-charged water, on reaching the roof of a cave, evaporates somewhat, and gives up some of its gas, with the result that part of the lime is deposited. After hanging for a time on the ceiling, the drop of water falls to the floor where much, or all, of the remaining lime is deposited. Many

repetitions of this process cause a long, slender, icicle-shaped incrustation of carbonate of lime, called a *stalactite*, to be built vertically downward from the roof of the cave, and a similar, though usually thicker, mass, called a *stalagmite*, to be built vertically upward from the floor. Many stalactites and stalagmites may form in a single cave, and some of them may join to form columns or pillars (Fig. 297). Wonderful and fantastic

Fig. 297
Stalactites, stalagmites, and pillars in a cave Oregon Caves, Oregon. (Photo by courtesy of the U S. Forest Service)

effects are thus often produced, dependent upon the manner in which the lime-charged waters trickle and spatter, as for example in the Luray Cave of Virginia; parts of Mammoth Cave, Kentucky; and Wyandotte Cave, Indiana. Stalactites and stalagmites occur in great profusion, and of great size — 5 to 25 feet in diameter, and 25 to 50 feet long — in the very recently explored Carlsbad Cave of New Mexico.

Under more exceptional conditions, stalactites and stalagmites may be formed of other minerals, such as chalcedony, limonite,

etc. These are rarer and usually much smaller than those of lime because the materials are more difficultly soluble.

Spring Deposits. — When underground water, highly charged with mineral matter, reaches the surface as a spring, there is a strong tendency for it to deposit at least part of its mineral load. Reduction of pressure, lowering of temperature, and escape of carbonic acid gas, are among the principal factors which cause such deposition by springs (Fig 288) Deposits of carbonate of lime are not uncommonly found around springs of even relatively cool water, where the mineral-charge is heavy. *Travertine* is a general name applied to limy spring deposits, while the more porous or stringy, limy masses are called *calcareous tufa.*

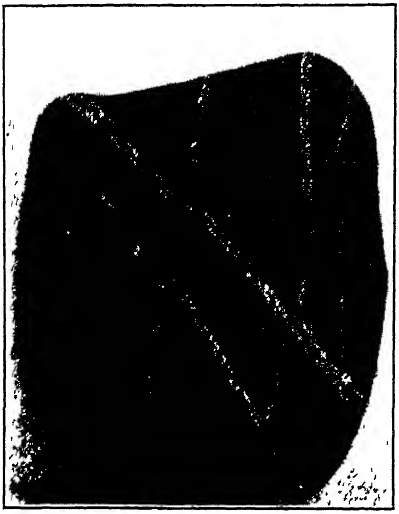

Fig. 298
Veins of calcite in a pebble of schist. (Photo by the author)

Large, hot springs are especially likely to yield extensive deposits in their immediate vicinities, an excellent case in point being the great accumulations of travertine around the Mammoth Hot Springs of Yellowstone Park (Fig. 288). The alkaline waters of the hot springs and geysers of the Yellowstone geyser basins bring much so-called *geyserite* to the surface where it accumulates. This porous material is the same in composition as the mineral quartz. Other mineral substances are less often deposited by springs.

Belt of Cementation; Veins. — Underground water accomplishes most of its work of solution in the upper portion of the zone of fracture, that is in the belt of weathering (p. 58). As the water moves downward, it becomes richer in mineral matter, and more sluggish. The tendency is for the dissolved substances to be deposited when they reach considerable depths, filling cracks, fissures, and openings of all kinds, even exceedingly small ones.

This portion of the zone of fracture, in which deposition of dissolved minerals takes place, is called the *belt of cementation.* Many sedimentary rocks are consolidated by cementation in this belt. Cracks and fissures filled with mineral matter from underground water solutions are called *veins* (Fig. 298). Among the very common vein-forming minerals are quartz, calcite, fluorite, and barite. Two or more minerals may occur in one vein. Where

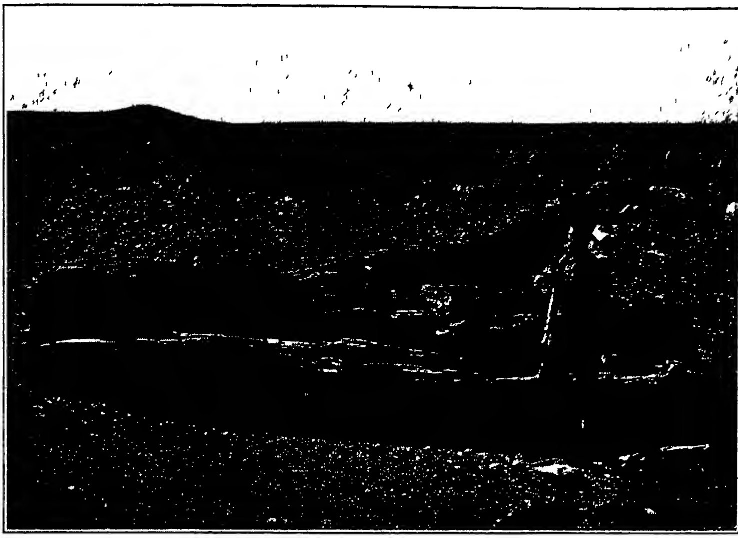

Fig 299

Petrified tree-trunks uncovered by erosion. Petrified Forest National Monument, Arizona. (Photo by G. P. Merrill, U.S. National Museum.)

underground openings are filled only partly with mineral matter, beautiful crystals often occur.

Valuable ores, such as those of gold, silver, copper, lead, and zinc, usually have been deposited from underground water solutions, and concentrated in veins in many regions. Deposition also often results where underground waters with certain substances in solution travel through various rocks, or encounter solutions of other substances, thus bringing about chemical reactions which may develop insoluble substances, with resultant deposition of the latter.

Mineral-charged subsurface water may also bring about *petrifaction*, that is, the replacement, particle by particle, or cell by cell, of a buried shell, log, or other remains of an organism by the mineral matter from an underground solution. In this manner the so-called Petrified Forests of Arizona (Fig. 299), of Yellowstone Park, and of other regions were formed, the petrifying material having been the very common substance called "silica," which is the same in composition as the mineral quartz.

CHAPTER XIII

MOUNTAINS, PLATEAUS, AND PLAINS

Principal Relief Features of the Land

General Statement. — The earth's relief features of first magnitude are the *continents* and the *ocean basins*. The principal relief features of the continents are *mountains*, *plateaus*, and *plains*. Many references to these have been made in the preceding pages, but our present purpose is to consider them briefly as units, with particular emphasis upon their origin and history. It has been well to reserve such a discussion of mountains, plateaus, and plains until late in our study of physical geology because it involves a knowledge of so many facts and principles of the science, more especially of diastrophism, vulcanism, and erosion, and also a knowledge of common rocks. Ocean basins have already been considered in Chapter X.

Mountains constitute the most conspicuous relief features of the earth. The expression " everlasting hills " may seem appropriate to the layman who is impressed by the grandeur and massiveness of mountains. To the geologist, however, mountains, even the grandest of them, are known to be but transitory forms. A mountain, like an organism, has a life history which may be relatively short and simple, or long and complex. Many of the most profound lessons of geology have been learned from the study of the tilted, folded, faulted, and deeply eroded rocks of the earth's crust where they are exhibited so wonderfully in mountains.

Definition of Mountains. — In the commonly accepted sense of the term, a mountain is any notably elevated portion of a region. As more precisely defined, " *mountains* are conspicuously high lands which have but slight summit areas " (R. D. Salisbury). Mountains are conspicuously high in a relative sense only, that is, they stand out boldly above their surroundings. Low mountains are often called *hills*, but the distinction between these two terms is often a relative matter, usually depending upon the region in

which the elevations occur. Thus in a region of low relief like Iowa, elevations of only 100 to 300 feet are sometimes referred to as mountains (e.g. Mount Vernon, Iowa), while in other regions elevations of 1000 to 3000 feet may be called hills (e.g. Berkshire Hills, Massachusetts). As a rule, however, elevated masses lower than a few hundred feet are not called mountains, and those higher than a few hundred feet are not called hills.

Definition of Plateaus. — Tracts of relatively high land with considerable summit, or near-summit, areas are called *plateaus*. They nearly always rise distinctly and rather abruptly above the surrounding country on at least one side. True plateaus rarely, if ever, merge into lowlands (plains). Plateaus are usually higher than plains, but they may be considerably lower, as for example the Piedmont Plateau of the eastern United States which is much lower than the Great Plains lying just east of the Rocky Mountains. Plateau surfaces are usually more or less trenched by valleys, or even great canyons; and mountains rise above the general level of some of them.

An excellent large-scale example of a high-level plateau with a conspicuous descent on one side is the great Colorado Plateau of the southwestern United States (Fig. 5). It lies from 5000 to 11,000 feet above sea level, with a gradual increase in altitude from south to north, and it is separated from the Great Basin on the west by a steep slope (fault scarp) 1000 to 3000 feet high. It is trenched deeply by the Grand Canyon of Arizona.

Some plateaus lie between plains and mountains. Examples are the Cumberland (or Allegheny) Plateau which lies between the Appalachian Mountains and the Interior (Mississippi) Plain, and the Piedmont Plateau which lies between the Appalachian Mountains and the Atlantic Coastal Plain (Fig. 5).

Some plateaus, like Greenland and the Iberian Peninsula (Spain and Portugal), rise abruptly either from the sea or from narrow coastal plains, on one or several sides.

The remarkably lofty plateau of Tibet (altitude, fully 15,000 feet) is almost surrounded by mountains, as is also the plateau of central Mexico.

Definition of Plains. — Tracts of relatively low, level lands are called *plains*. In actual usage the terms "plains" and "plateaus" are often confused, and, as a matter of fact, a very clear distinction between them is difficult to make. Plains are,

as a rule, lower than plateaus, but there are striking exceptions, as for example the Great Plains of the United States lying at altitudes of from 3000 to 6000 feet, and gradually descending eastward into the Interior (or Mississippi Valley) Plain (Fig. 5). Relation to the surrounding country is a more important criterion than altitude for distinguishing between plateaus and plains. Thus if the region known as the Great Plains were separated abruptly from the Interior Plain, or if it were almost surrounded by mountains, some such term as "Great Plateau" would be more appropriate.

Much of the continental areas are occupied by plains. Not only are plains the simplest of land forms, but also they are the most widespread. Most of the people of the world by far live upon plains. In the United States, plains are excellently and extensively illustrated by the Interior (Mississippi Valley) Plain, the Great Plains, and the Atlantic and Gulf Coastal Plains (Fig. 5). The Great Plains are remarkably smooth, but the others mentioned are considerably trenched by stream-cut valleys.

Arrangement of Mountains

A *mountain peak* is a more or less cone-shaped mountain mass, as for examples Lassen Peak, Pikes Peak, Mount Rainier, and Mount Washington.

A *mountain ridge* is a relatively long, narrow mountain mass, such as the Blue Ridge and many others, often locally called mountains or ranges, in the Appalachian district.

Peaks or ridges, or both, may be grouped irregularly, as in the Adirondack and Catskill Mountains of New York. A single large ridge may be surmounted by a number of peaks, as for example the Cascade Range. A single large ridge may be without very conspicuous peaks at its crest, as for example the Sierra Nevada Range. Many nearly parallel ridges may be grouped into long, relatively narrow belts, as in the case of the Appalachian Range.

A *mountain range* may, from the geological standpoint, best be regarded as a single mountain ridge, or group of ridges and peaks, often with more or less parallel arrangement, the material of which was built up into mountain form by a geological process (or set of processes) during a particular portion of geological

time. In dealing with mountain origin and structure, the range is, therefore, a geological unit. The Appalachian Range, the Sierra Nevada Range, the Wasatch Range, the Coast Range, the Pyrenees, the Alps, and the Himalayas are good examples, though it should be borne in mind that most of these were rejuvenated after their original uplift.

A *mountain system* "consists of two or more mountain ranges, of the same (or nearly the same) period of origin, belonging to a common region of elevation, and generally either parallel, or in consecutive lines" (J. D. Dana). Thus the Laramide system includes a series of ranges in the Rocky Mountains.

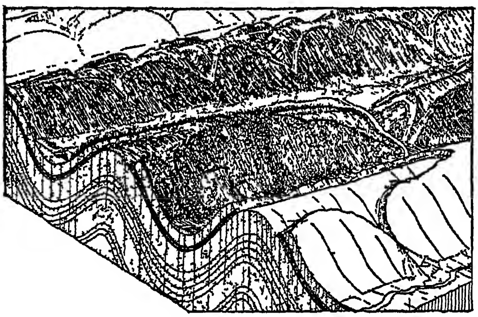

Fig 300

Diagram and section showing slightly eroded mountain ridges Jura Mountains, Switzerland. (After W M. Davis.)

A *mountain chain* consists of two or more systems or ranges formed at distinctly different geological times in a definite part of a continent, and usually more or less parallel. Thus the Appalachian Chain comprises the whole mountain region on the Atlantic side of North America, including the Acadian Range of Nova Scotia and New Brunswick, the mountains of eastern New England, the Green Mountains, the Berkshire Hills, the Highlands of the Hudson, and the Appalachian Range.

A *cordillera* is a grand combination of chains, systems, and ranges in one general portion of a continent. The North American Cordillera includes all the mountains from the eastern face of the Rocky Mountains to the Pacific Ocean.

Origin of Mountains

Folded Mountains. — *Character, origin, and structure of the materials.* Most of the great mountain ranges of the earth belong in the category of so-called *folded mountains.* Folding of strata,

accompanied by general uplift, is the most important of the various modes of origin of mountains. A good idea of the general character, origin, and structure of the materials of a typical folded range

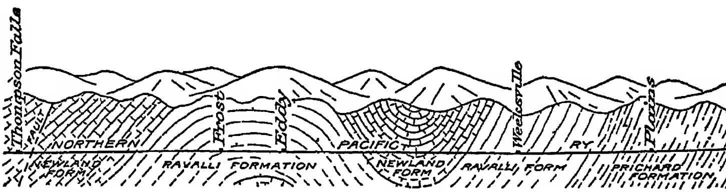

Fig. 301

Structure section 30 miles long showing deeply eroded folds. Rocky Mountains of Montana (After U. S Geological Survey)

may be gained from the consideration of a carefully studied example, such as the Appalachian Range

Even a casual trip across the Appalachian Range would reveal the fact that the rock materials consist very largely of common kinds of stratified rocks, that is, sandstones, conglomerates, shales, and limestones It would also be evident that the thickness of the strata must be measured by thousands of feet. As a matter of fact, careful determinations have shown that the strata of the Appalachians were accumulated originally under water, layer upon layer, to a maximum thickness of 25,000 to 35,000 feet.

Fig. 302

Structure section showing deeply eroded folded strata in the Appalachian Mountains of West Virginia C = Cambrian, O = Ordovician; S = Silurian, D = Devonian Length of section, 18 miles. (After Darton, U S. Geological Survey)

The tremendous thickness of such a pile of strata clearly leads to the conclusion that the deposition must have continued for millions of years. Not only are the rocks of the Appalachians water-laid sediments of great thickness, but also they were deposited mostly under sea water as proved by the fact that they contain numerous fossil remains of typical marine animals.

The strata of a typical folded range, like the Appalachians, are largely, or wholly, of shallow-water origin, that is, they were laid down on the floor of a relatively shallow sea. This is proved by the very nature of the materials, particularly the sandstones and conglomerates; by the types of animals represented in fossil form; and by certain markings on many strata, such as ripple marks, mud cracks, etc. Since the strata are of shallow-water origin, and since they are piled up to a great thickness (many thousands of feet), it is obvious that the sea floor upon which the sediments accumulated must have subsided during the process

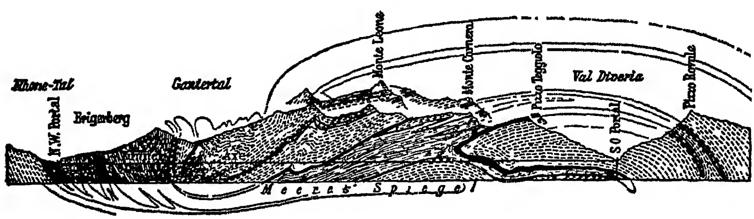

Fig 303

Structure section showing the deeply eroded, very highly folded Alps along the line of the Simplon Tunnel Length of section, 16 miles (Kayser, after Heim)

of deposition. Such deposition of sediments usually takes place in a great down-warp, or subsiding trough, generally hundreds of miles long and 75 miles or more wide, known as a *geosyncline* to distinguish it from an ordinary syncline.

The folded strata of a typical folded range are nearly always arranged in relatively long, narrow belts or zones. This is because they consist very largely of land-derived materials which were deposited in shallow water along the margin of a land area This is in harmony with the well-known fact that, at the present time, land-derived sediments (gravel, sand, and mud) are deposited almost entirely within 100 to 200 miles of the continents. We must, therefore, think of the site of a typical folded range as once having been a subsiding, marginal sea bottom upon which sediments piled up layer upon layer for millions of years to a thickness of many thousands of feet.

One of the most strikingly evident features of a typical, folded range is that the strata are not in essentially horizontal

position as they were when they were deposited, but that they have been much disturbed and thrown into folds. Single folds range in length and width from less than a few feet to miles (Figs. 92 and 301). The degree of folding varies from gentle anticlinal and synclinal structures to overturned and recumbent folds, and even to compressed isoclinal folds (Figs 84 and 88). Such folded structures were, as previously explained (p 112), developed by a tremendous force of lateral compression within the zone of flowage of the earth's crust. The folds are now exposed as a result of removal of overlying material by subsequent erosion The main axes of the folds, with some minor exceptions, extend essentially parallel to the main trend of a folded range. This is because the force of compression was exerted at right angles to the trend of the range.

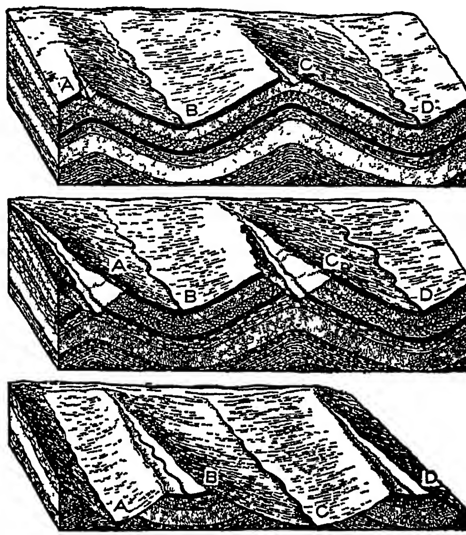

Fig. 304

Block diagrams showing how erosion may cause anticlinal valleys and synclinal mountains. (From Tarr's New Physical Geography, by permission of the Macmillan Company.)

A high degree of folding of strata results in a considerable amount of earth-crust shortening. This is because the belts of once horizontal strata are crumpled into much narrower zones. It has been estimated that the crustal shortening caused by the Appalachian folding across southern Pennsylvania was fully 26 miles. In the very severely folded Alps the shortening is much greater.

Brief history of a folded range. In dealing with a cycle of erosion or topographic development, we used the terms infancy, youth, maturity, and old age. In a somewhat similar manner we may use a biological analogy in dealing with the evolution of a typical,

folded range. First there is the *embryonic stage* during which the sediments accumulate upon the marginal sea floor. This stage is usually very long — millions of years at least.

Next comes the *birth* of the range when the strata are subjected to lateral pressure, somewhat folded, and raised partly out of the sea.

During the *youthful stage* the mountain range grows, that is, it increases in altitude, and the folding becomes more complex,

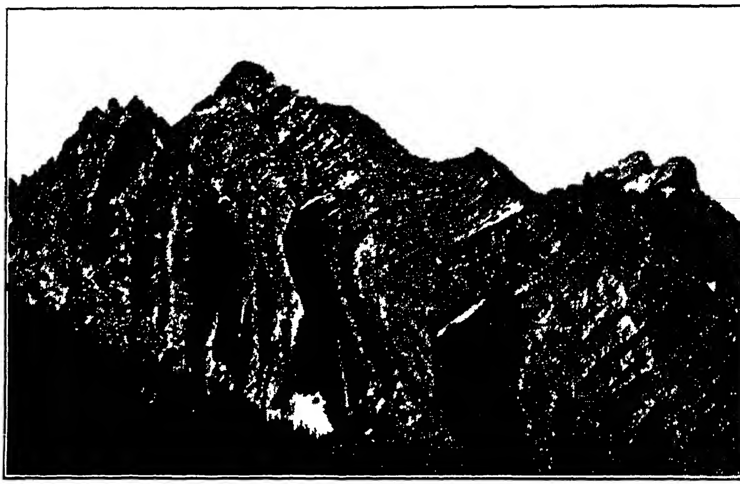

Fig 305

A mountain ridge carved out of highly inclined, folded strata Height of mountain, about 2000 feet. (Photo by Chapman for U S. Geological Survey.)

because the compressive force is still very active. The increase in height takes place because the constructive force of uplift is greater than the destructive force of erosion, which latter already operates to cut down the range.

The *mature stage* is reached when the upbuilding process is about equalled by the tearing down (erosive) process. It is during this stage that the range exhibits its greatest altitude and its maximum ruggedness of relief.

During the *old-age stage*, the upbuilding process either greatly diminishes, or ceases altogether, and the tearing down process of erosion causes a steady reduction in the height of the range.

Finally the *extinction* of the range, as a conspicuous relief feature, is reached when erosion has reduced it to the condition of a peneplain.

The normal order of events in the history of a folded range, as above outlined, may be interrupted at any stage by renewal, or accentuation, of uplift, particularly after maturity, causing a revival of stream activity, and an increase in ruggedness of relief. Even after a range has been peneplaned it may be uplifted and rejuvenated with establishment of a new cycle of erosion. Subsidence would directly cause a lowering of the range and a slowing down of the process of erosion.

Fig 306
Mountains carved out of highly folded strata. Folds not visible in picture. Selkirk Mountains near Glacier, British Columbia (Photo by the author)

Rate and date of folding. It must be clearly understood that folding and uplift of a great body of strata into a large mountain range is a very slow process, generally requiring hundreds of thousands, or even some millions, of years. As compared to the long eons of known geological time, the active process of folding does, however, take place within a comparatively short time. It is usually much less than the time necessary for the deposition of the strata. Great mountain ranges have been formed by folding of rocks at various times, and in many places, during geological time. Such mountain-making (orogenic) disturbances are commonly called "revolutions." Thus, in North America, since the opening of the Paleozoic era, some of the most important orogenic disturbances have been as follows: Taconic Revolution, in western New England and southeastern New York, toward the close of the Ordovician period (see table, p. 7); Appalachian Revolution toward the close of the Paleozoic era; Sierra Nevada Revolution toward the close of the Jurassic period; Rocky Mountain Revolution toward the close of the Cretaceous period;

and the Coast Range Revolution in the midst of the Tertiary period.

How is the date of a folded range determined? Two principles are involved. First, it is necessary to determine the geological age of the latest (youngest) strata involved in the folding. The folding must have occurred *after* the deposition of such strata. Second, it is necessary to determine the geological age of the oldest (lowest) non-folded, or less folded, strata resting (by un-

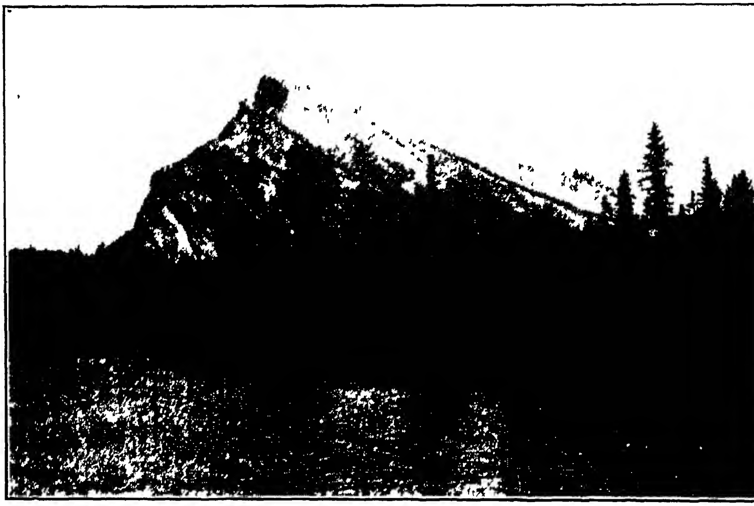

Fig. 307

A mountain ridge carved out of strongly tilted strata. Near Banff, Alberta, Canada (Photo by Miss A. A. Heine)

conformity) upon the folded rocks. The folding of the underlying rocks must have taken place *before* the deposition of the overlying strata (Fig. 309). To use a concrete example, we know that the Appalachian Revolution occurred at about the close of the Paleozoic era because the youngest folded strata are of very late Paleozoic age, while the oldest non-folded strata, resting upon the folded rocks, are of early Mesozoic age.

Cause of folding. We are reasonably certain that the earth does not consist of a molten interior covered by a solid crust but rather that it is composed of a great, hot, solid interior enveloped by a relatively cool, outer, or crustal, portion. Mountain-

folding, with its accompanying crustal shortening, is quite certainly produced by lateral pressure within the earth's crust. It seems to be a well-established fact that the earth has been a shrinking body for long ages of geological time. It also seems to be clear that orogenic, or mountain-folding, forces are somehow caused by earth contraction with its resultant stresses and strains in the shell (or crust) of the earth.

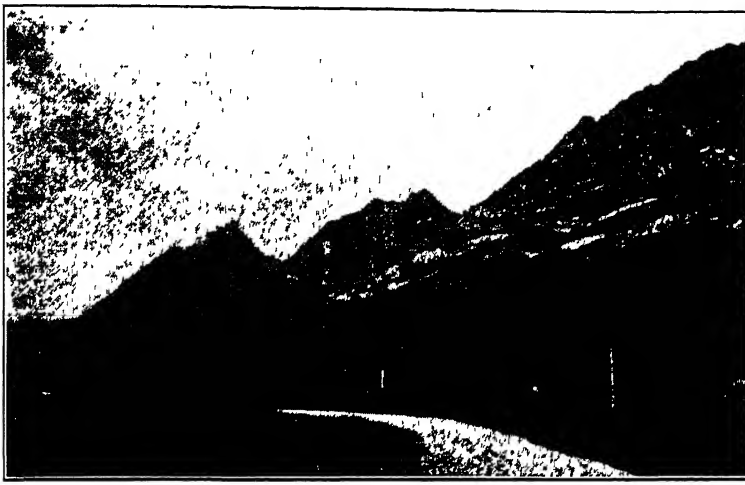

Fig 308
A mountain ridge carved out of vertical strata. Near Banff, Alberta, Canada. (Photo by the author.)

The ultimate cause of earth contraction is not known. It may be due to loss of heat from the interior, or to the force of gravity whereby the crust is pulled nearer and nearer the center of the earth, or to both. Just how earth contraction produces folding of rocks to form mountain ranges is not yet definitely known. It would carry us too far afield to discuss at all fully the various phases of these problems. A few brief suggestions only will be given. The whole matter is complicated by the facts that the crustal portion of the earth is a heterogeneous mass, and that folding of strata has been localized both in place and time, that is, folded mountains have formed in various regions, and in various parts of geological time.

According to one view, conduction of heat from the interic portion of the earth outward would cause " a severe crowding c the outer (crustal) zone upon itself in shrinking to fit the dee interior as it loses heat and shrinks." Local, relatively wea zones of the crust would yield to such crowding action by crumplin and folding.

Another view is that the crowding action of the crust upo itself may be largely, or wholly, due to the force of gravity whic acts powerfully to cause all material of the lithosphere to mov toward the center of the earth. Weaker portions of the crus would, therefore, be folded.

According to the doctrine of *isostasy*, the lithosphere is in condition of approximate equilibrium at any given time. Th lithosphere consists of heterogeneous material varying consider

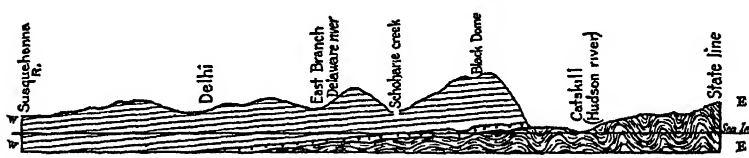

Fig 309

Structure section illustrating the date of folding of strata The folded rock are Ordovician and older; the non-folded rocks are Silurian and Devoniar Catskill Mountains, New York (By the author)

ably in density. Those segments of the lithosphere which consis of heavier material are lower because they are drawn down mor powerfully by gravity toward the center of the earth, while th lighter segments stand out in relief. The two grand continenta segments, and the two grand oceanic segments, are thus explained These grand segments are, in turn, believed to be subdivided int smaller segments of varying sizes and densities. According to th theory of isostasy, earth segments of comparable surface area tend to contain the same weight of material irrespective of volume If, through erosion, much material is transferred from a higher lighter segment to a lower, heavier segment, rock material a great depth will flow from the heavier segment into the lighter thus restoring the equality of material in the segments. Th heavier segment thus sinks, while the lighter segment rises Relatively near the surface, material cannot be transferred readily

from the heavier to the lighter segment, and so the crowding action of one against the other may cause there a crumpling or folding of the rocks. In harmony with this view is the fact that many great folded ranges have formed along the general borders of the continental and oceanic segments.

According to another explanation, much folding of strata is ascribed to intrusion of great volumes of magma into the earth's crust. Igneous activity is certainly a common accompaniment of

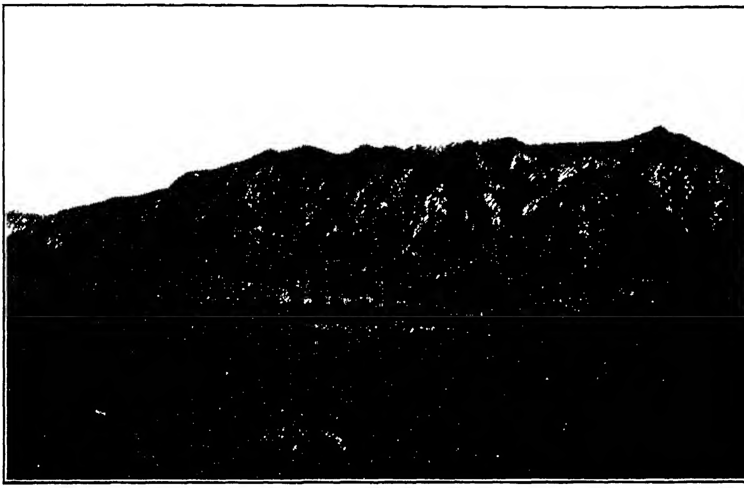

Fig 310

Part of a great, somewhat eroded fault scarp about 5000 feet high (Wasatch Mountains, near Ogden, Utah (Photo by the author.)

mountain folding, and its crowding (or shouldering) action has been deemed by some a sufficient cause of crumpling of adjacent strata.

Faulted (Block) Mountains. — Many mountain ranges are caused either partly or wholly by faulting, whereby great earth blocks are made to stand out in relief. Such blocks are often tilted, and they are called *faulted or block mountains*. Tilted block-mountains are developed typically in southeastern Oregon (Fig. 319) where a series of them from 10 to 40 miles long, and 1000 feet or more high, have their fault scarps affected only slightly by erosion. Many of the north-south ranges of Nevada and Utah

are block mountains considerably modified by erosion. The bold western face of the Wasatch Range of Utah is a moderately eroded fault scarp about a mile high, and many miles long (Fig 310). Grandest of all in the United States, however, is the Sierra Nevada Range which is a single, great, tilted, fault block over 500 miles long, and from 60 to 100 miles wide. A somewhat eroded very steep, fault scarp, ranging from a few thousand feet to two miles high, sharply bounds the range on the east side, while a long relatively gradual slope forms its western side (Fig. 154). A

Fig 311

A great volcanic cone considerably eroded Mt Shasta, California. (Photo by Diller, U. S. Geological Survey)

portion of the Rhine Valley of Germany is a sunken fault block lying between two tilted fault blocks — the Vosges and the Black Forest.

Volcanic Mountains. — We have already learned that many mountain peaks, often of great height, have been built up by accumulations of igneous materials around the vents of volcanoes. A few among the many well-known examples are: Lassen Peak, California (over 10,000 feet high); Mount Shasta, California (over 14,000 feet); Mount Rainier, Washington (over 14,000 feet); Cotopaxi in Ecuador (nearly 20,000 feet); and Mauna Loa in Hawaii (about 30,000 feet, as measured from the sea bottom on which it stands).

Not only individual peaks, but also whole mountain ranges may be built largely, or wholly, by volcanic action. Thus the Cascade Range, extending for hundreds of miles from northern California through Oregon and Washington into British Columbia, is essentially a volcanic range whose once greatest centers of activity are marked by conspicuous cones like Mounts Lassen, Shasta, Pitt, Hood, St. Helens, Rainier, and Baker. The Chain of the Aleutian Islands of Alaska, more than a thousand miles long, is an excellent illustration of a mountain range now being built in the sea by active volcanoes. The Hawaiian Islands represent the highest parts of a great, largely submarine, volcanic range hundreds of miles long.

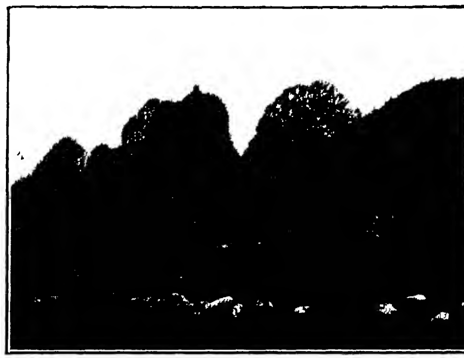

Fig. 312
Mountain peaks several thousand feet high carved out of horizontal strata Zion Canyon, Utah (Photo by the author)

Laccolithic Mountains. — Closely related to volcanic peaks in origin are so-called *laccolithic mountains*, the principle of which has already been described (p 141). In such cases molten material is forced into the crust of the earth, but instead of reaching the surface, it bulges or lifts the upper portion of the crust into dome-like forms. Laccoliths are very typically illustrated in southeastern Utah, and also in parts of Colorado, Wyoming, and South Dakota, in all of which regions practically horizontal strata have been bulged up by magmas. There they show all stages of erosion from those whose covers are practically intact to others whose igneous cores have been more or less laid bare, with the eroded edges of strata lapping up on their flanks (Fig. 123). Laccolithic mountains are neither abundant nor very large. They occur singly, or in groups, but practically never in the form of distinct ranges.

Erosion Mountains. — All mountains are of course subjected to, and modified by, erosion. In not a few cases, however, moun-

tains may be developed by erosion alone in uplifted regions little, if any, affected by folding, faulting, or igneous activity. Such so-called *erosion mountains* are formed by the erosive sculpturing of plateaus and high plains into high ridges, peaks (or buttes), mesas, and deep valleys. The Catskill Mountains of New York, with their numerous narrow ridges and deep valleys, have been carved out of upraised, nearly horizontal strata simply by erosion.

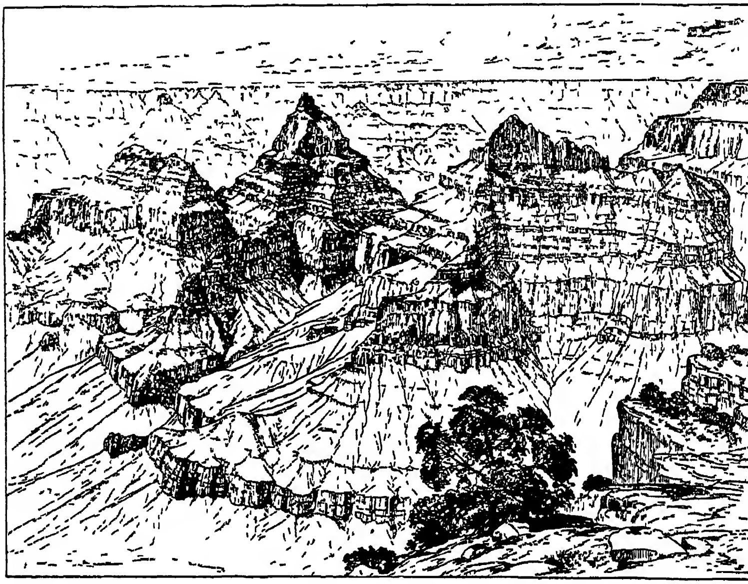

Fig 313

Mountainous masses several thousand feet high carved out of nearly horizontal strata. Grand Canyon, Arizona (After Holmes, U S. Geological Survey.)

The maze of sharp mountain ridges and narrow valleys constituting the badlands of parts of Wyoming and South Dakota, have been eroded out of high, relatively soft, nearly horizontal strata (Fig. 125). The numerous peaks and pinnacles which rise mountain-like within the Grand Canyon of Arizona (Fig. 313) are really erosion remnants, or erosion mountains. Another good illustration of erosion mountains is near the mouth of Zion Canyon, Utah, where mountain peaks several thousand feet high have been

carved by erosion out of horizontal strata lying from 4000 to 8000 feet above sea level (Fig. 312).

Composite Mountains. — In addition to erosion which affects all mountains of whatsoever mode of origin, folding, faulting, and igneous activity may all play important parts in the development of a single mountain range. This was true of the Appalachian Range, especially its southern portion. The severe folding of the original Sierra Nevada Range was accompanied by tremendous intrusions of granite magma, as well as by vigorous erosion. Faulting and erosion only have entered into the development of the block mountains of southeastern Oregon. Many mountains are wholly of igneous origin, and more or less modified by erosion.

Various mountain ranges formed by folding have been deeply eroded, and then rejuvenated by uplift without notable folding or faulting. Examples of such rejuvenated ranges are given beyond.

Sculpturing and Destruction of Mountains

From the very beginning of its history as a topographic feature, every mountain mass is attacked unceasingly by weathering and erosion which continue to operate during the periods of youth, maturity, and old age. In the course of time every mountain will be leveled by erosion unless it is rejuvenated by some process of igneous activity or diastrophism. Cases of rejuvenation are described under the next heading.

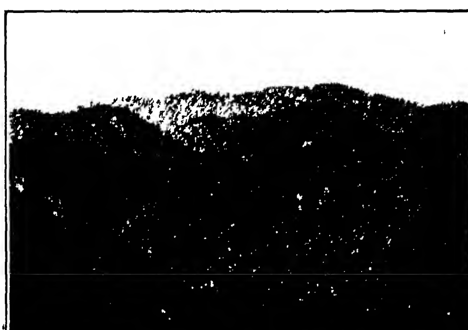

Fig. 314

Mountains carved out of igneous and metamorphic rocks. San Gabriel Mountains, California. (Photo by the author.)

All three of the great erosive agents — water, ice, and wind — are important in the sculpturing of mountains, but water is the most effective. The principles of weathering, and of water, ice,

and wind erosion, as well as many topographic forms resulting from their action, are described in preceding chapters, and it seems unnecessary to repeat them here in their direct bearing upon mountain sculpturing. Some general effects of the action of running water will, however, be mentioned. Thus a range consisting of well-defined more or less parallel folds will, in maturity, or after rejuvenation, be eroded into a system of parallel ridges and valleys (e.g. the Appalachian Range). A mountain mass consisting of approximately horizontal strata (e.g. the Catskill Mountains), or of igneous or metamorphic rocks without well-defined structures (e g. the western Adirondack Mountains) will be carved into a maze of valleys and ridges. Conspicuous valleys will often develop along lines of prominent faults (e.g. the eastern Adirondacks, and the Coast Range Mountains). Volcanic and laccolithic peaks will be trenched deeply with valleys radiating from near their summits (e.g. Mount Shasta). Block mountains will be dissected variously by erosion depending upon the attitude of the blocks, and the character and structure of their rocks. Great tilted blocks will, in youth and maturity, have a system of approximately parallel canyons carved out of their long, more gradual slopes, and short steep gorges and canyons in their fault scarps (e.g the Sierra Nevada Range).

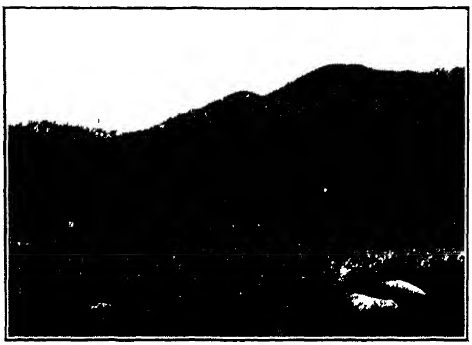

Fig 315

Mountains carved out of igneous and metamorphic rocks, showing mature topography. Adirondack Mountains, near Loch Muller, New York. (Photo by the author.)

In cold, humid regions, mountains may be sculptured considerably by glaciers which cause development of U-shaped valleys, cirques, and knife-edge ridges (e.g. Glacier Park, Montana).

The action of wind is an erosive factor usually of considerable importance in mountains in arid regions (e.g. the Great Basin mountains of Nevada and Utah).

Rejuvenation of Mountains

The history of many mountain ranges is more or less comple A range may be born and pass through the mature and old-ag stages to extinction (peneplain stage) practically without interrup tion. It may, or may not, then be rejuvenated by diastrophisr or igneous activity. A range may have its normal life histor interrupted at some particular stage, or during more than on stage. The more the great ranges are being studied, the more it is realized that the life histories of many of them are by no means regular and simple. A few examples of interrupted cycles of mountain history will serve to make clear the general principles.

Fig 316

A mountain peak carved out of massiv granite. Tehipite Dome, Kings Rive Canyon, California (Photo by courtes of the U S Forest Service)

The Rocky Mountains were elevated and more or less folded (Fig. 301) toward the close of the Mesozoic era, giving rise to the so-called Rocky Mountain Revolution. This revolution inaugurated a period of volcanic activity which affected the mountains considerably during th Tertiary period. In the early Tertiary period there was a notabl renewal of folding, especially in Utah, Wyoming, and Montana Also in early Tertiary time, considerable faulting occurred, par ticularly the development of the tremendous thrust fault alon the eastern side of the Rockies in southern Canada and th northern United States (Fig. 114). In late Tertiary time, an possibly even later, at least one profound movement of uplif accompanied by faulting, but with little or no folding, greatl rejuvenated the Rockies which had been much reduced b

erosion. Most of the detailed sculpturing of the mountains has been accomplished since the rejuvenation by rivers and glaciers, during the present (Quaternary) period of geologic time.

The Sierra Nevada Range was severely folded and elevated toward the close of the Jurassic period. Great volumes of granite magma were intruded at the same time. Erosion then held sway until the range was reduced to hills by middle Tertiary time. Then a great fault fracture (already described, p. 135) began to develop

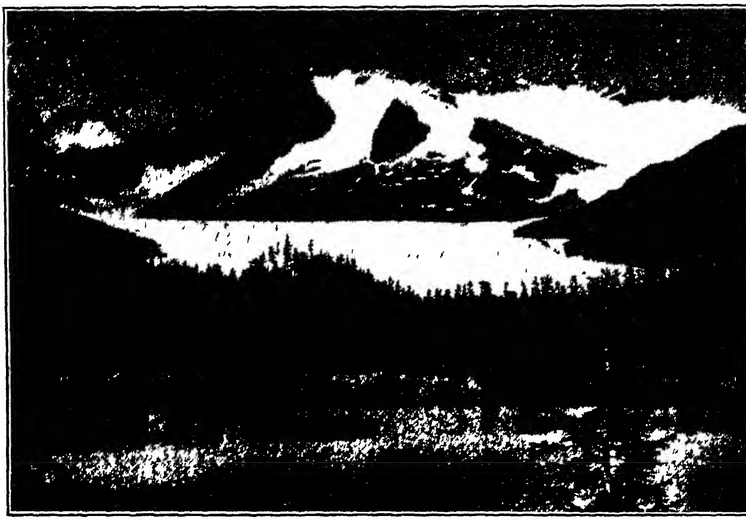

Fig. 317

Mountains being sculptured by glaciers. Mendenhall Glacier, near Juneau, Alaska (Photo by E. Andrews, Douglas, Alaska.)

along the eastern side, and the whole Sierra Nevada fault block has been upraised and tilted into its present position. The many deep canyons, like Yosemite, Kern River, King's River, American River, and Feather River, have been cut into the western slope of the fault block by erosion (Fig. 154).

The Cascade Range was considerably folded and elevated toward the close of Jurassic time, and then eroded. During Tertiary time the range was rejuvenated profoundly by volcanic action, including the development of the series of great cones (already mentioned) arranged along its summit (Fig. 270). In

early Quaternary time, at least that portion of the range cut through by the Columbia River was bowed up several thousand feet in the form of a broad anticline with its axis parallel to that of the range, the river maintaining its course during the uplift (Fig. 161).

The Appalachian Mountain district was subjected to several minor, more or less local, uplifts during the Paleozoic era, but the grand climax (Appalachian Revolution) of folding and uplift occurred toward the close of the era (Fig. 302). Accompanying, and shortly following the folding, great thrust faults developed. Throughout Mesozoic time, the range was subjected to profound erosion, and reduced to the condition of a peneplain. About the beginning of the present (Cenozoic) era, the whole peneplaned region was rejuvenated by irregular uplift and warping, but without real folding. The amount of uplift usually varied from 1000 feet to several thousand feet. The existing ruggedness of the range is due to erosion which has operated upon the rejuvenated range (Fig. 318). The system of long, narrow mountain ridges and valleys has been determined by the harder and softer rock formations which follow the strike of the original folds.

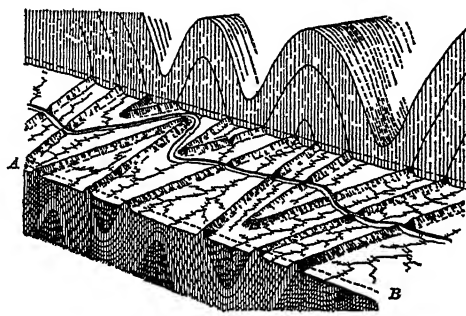

Fig 318
Block diagram illustrating the history of the Appalachian Range (After W M Davis)

Origin and History of Plateaus

Some of the most important modes of origin of great plateaus are the following: (1) By simple uplift with little or no tilting, faulting, or folding, good examples being the plateau of southwestern New York, and the Allegheny Plateau just west of the Appalachian Range; (2) by uplift with tilting and some faulting, but with little or no folding, an excellent case in point being the

great Colorado Plateau, and (3) by the up-building of a region by many out-pourings of lava, as illustrated by the Columbia Plateau of the northwestern United States. Smaller plateaus (or table lands) may originate by being faulted above the surrounding country, as illustrated by several examples along the southern side of the Adirondack Mountains of New York; or by cutting down the surrounding country by erosion, good examples being the Tug Hill Plateau between Lake Ontario and the Adirondack Mountains, and many mesas of the southwestern states.

Plateaus, as well as mountains, are attacked by weathering and erosion from the very beginning of their history By maturity, the original, more or less flat, surfaces are much trenched and dissected by erosion, giving rise to maximum ruggedness of relief. They are then often called mountains (e g. Catskill Mountains) instead of plateaus. With continued erosion, plateaus become more subdued in relief, and they are worn down finally to peneplains. As in the case of mountains, so with plateaus, the normal cycle of topographic development may be interrupted by rejuvenation.

Origin and History of Plains

Extensive plains may originate by simple uplift accompanied by little or no tilting, warping, or folding. A good example is the wide Interior Plain of the Upper Mississippi Valley which is nearly everywhere less than 1000 feet above sea level, and considerably dissected by erosion.

Great plains may originate by uplift accompanied by notable tilting, as for example the Great Plains area which inclines downward, from an altitude of a mile or more at the base of the Rocky Mountains to a thousand feet or less, within a distance of several hundred miles eastward (Fig. 5). The Great Plains are affected relatively little by erosion.

Plains of great extent may be formed by emergence of a marginal sea bottom, without notable folding, faulting, or warping, either by uplift of the land, or by withdrawal of the sea, or by both. Wonderful examples are the Atlantic and Gulf Coastal Plains of the United States (Fig. 5). During the uplift, which was the prime factor in their production, these plains were tilted seaward. They have been dissected considerably by erosion, though many wide, smooth areas remain.

Wide plains which result from long-continued erosion of land are called peneplains (p. 184). Many extensive peneplains are known to have developed during geological time, but good examples are rare at present because nearly all of those of fairly recent origin have been rejuvenated by uplift. Good examples of such upraised peneplains are those of the Appalachian and southern New England districts. Such uplifted peneplains are best classed among plateaus.

Glacial drift surfaces are often smooth enough for considerable distances to be called plains. A fine illustration is the broad, flat deposit left by the last ice sheet from central to northern Iowa.

Many relatively small plains are floors of extinct lakes which were built up and smoothed off either by deposition of sediment, or by mineral matter from solution. An exceptionally fine, large-scale example is the floor of the great glacial Lake Agassiz (p. 381).

Rivers form flood plains by deposition and lateral erosion (p. 160), and delta plains by deposition.

Plains may be modified by erosion, diastrophism, vulcanism, or deposition of material. High, or steeply inclined, plains can be affected very profoundly by erosion. High plains, like mountains and plateaus, reach maximum ruggedness of relief during the mature stages of their erosional history. Low plains, by their very position, can be affected but little by erosion. It is an interesting fact that an extensive low-lying plain may last much longer without notable change than a great mountain range.

CHAPTER XIV

ORIGIN AND HISTORY OF LAKES

General Features

A *lake* is an inland body of standing water. Either its water may be stationary, or it may have a moderate current through it. Lakes always occur where the surface drainage is obstructed. Two necessary conditions are basinlike depressions, and sufficient water to at least partly fill them. Lakes may consist of either fresh or salt water. Fresh-water lakes always have outlets. Some lakes are rather inappropriately called "seas," as for example the Dead Sea of Palestine.

Lakes vary in size from tiny ponds to sheets of water covering many thousands of square miles, though probably not more than a dozen in the world occupy areas of over 10,000 square miles. Largest of all is the Caspian Sea with an area of 169,000 square miles. The second largest is Lake Superior, covering nearly 31,000 square miles. Next in order of very great size are Lake Victoria-Nyanza in Africa (30,000), Aral Sea in Asia (26,900), Lake Huron (22,322), and Lake Michigan (21,729).

Lakes are known to vary in depth from a few inches to a maximum of 5618 feet in Lake Baikal of Siberia. The Caspian Sea has a depth of at least 3200 feet. Crater Lake, Oregon, with a depth of nearly 2000 feet, is probably the deepest lake in North America. The depth of Lake Superior is 1008 feet. Relatively very few lakes are over 1000 feet deep, and the vast majority of them are less than 100 feet deep.

Most lakes by far lie above sea level at all altitudes up to many thousands of feet. A remarkable case is Lake Titicaca (area, 3200 square miles) in South America at an altitude of 12,875 feet. The highest large lake in the United States is Yellowstone Lake at 7741 feet. Lake Tahoe on the California-Nevada line lies at 6225 feet.

The surfaces of some large lakes lie below sea level, examples being the Dead Sea of Palestine (−1300 feet), the Caspian Sea (−85 feet), and the Salton Sea of California (−249 feet).

The bottoms of a number of large lakes are well below sea level, a few examples being Lake Baikal (−4000 feet or more), Lake Ontario (−491 feet), Lake Chelan in Washington (−421 feet), and Lake Superior (−402 feet).

Most lakes in humid regions have surface outlets, that is, there is usually sufficient water to cause them to overflow the lowest parts of their basins rims. Such lakes consist of fresh water. In arid regions lakes usually do not have outlets, both because of the scanty volume of water, and the high rate of evaporation. Many depressions in arid regions contain no water at all, while others, called *playas*, hold water only temporarily, that is for greater or less periods after rains. Arid-region lakes with no outlets almost invariably contain salt (or alkaline) water.

As compared to the many millions of years of the known history of the earth, lakes, excepting possibly the largest and deepest ones, are short-lived, most of them exceedingly so. This is because they are merely temporary obstructions to drainage, and are soon destroyed by one or more of several processes as explained beyond in this chapter.

Geological Functions of Lakes

Some of the most important geological functions of lakes are the following: (1) Most of the sediments carried into lakes by streams or other agencies, settle on their floors. Lakes with no outlets act as perfect settling basins, but even where there are outlets, a great many lakes are effective settling basins. Thus the mighty Niagara River, which drains the four upper Great Lakes, is remarkably clear as it leaves Lake Erie. In other words, practically none of the sediment carried into the four upper lakes leaves them. A remarkable case is Lake Geneva in Switzerland which receives the very muddy Rhone River, and which discharges through a wonderfully clear stream. A very large amount of material accumulates in the lakes of the world each year, but it is much less than the quantity which is deposited on the sea floor. The filtering action of lakes causes the outlet streams to be less effective agents of erosion because, on leaving the lakes, they are lacking in grinding tools (sediments).

(2) Lakes act as storage reservoirs for surface drainage, and so they tend to regulate the volumes of streams which flow out of

them, furnishing a check upon destructive floods. The rate of erosion is thus affected because, as we have already learned, streams are usually most effective in their power to erode in times of flood. With slow-moving graded streams, there would be less tendency to develop wide flood plains, and, as a result of the settling-basin effects of lakes, such streams would deposit less material upon their flood plains.

(3) Larger lakes, or numerous smaller ones, tend to increase the rainfall, and also to keep the temperature of a region more uniform, making summers cooler and winters milder. This is well illustrated in the regions bordering Lakes Erie and Ontario on the south and southeast. Such climatic influences of lakes are of real importance because various geological processes, like weathering and erosion, are thereby affected.

(4) Plants, or shell-bearing animals, or both, are abundant in many lakes. Their shells, skeletons, or partly decayed remnants accumulate in the lake basins, thus helping to fill them. Such materials, found in fossil form in old lake deposits, often yield valuable evidence as to the nature of certain phases of the life of the geological times, as far back as millions of years ago, when the particular lakes existed.

(5) Considerable work of erosion is accomplished by waves cutting into parts of the shores of many lakes, the materials eroded being spread over the floors of the basins.

(6) When lakes with no outlets evaporate in arid regions, the various salts held in solution are deposited in layers or beds over the sites of the lakes. There are many examples of such deposits in the arid region of the western United States.

Origin of Lake Basins

Lake basins originate in many ways Our present purpose is to explain most of the more common, important, and interesting modes of origin of lake basins, and to describe briefly some illustrative examples.

Basins Formed by Diastrophism. — *By faulting.* When a block of the earth's crust sinks or rises relative to an adjacent block through the process of faulting, a troughlike basin often results. There are many examples in the Great Basin region of the western United States. A small basin, now partly filled with

water, formed in 1872 as a result of a sudden renewed movement of 20 to 30 feet along a fault near the base of the Sierra Nevada Range in the Owens Valley of southeastern California. Albert and

Fig 319

Structure section illustrating the origin of lake basins by faulting. Albert and Warner Lakes, Oregon (After Russell, U. S. Geological Survey)

Warner Lakes of southern Oregon are very typical cases of lakes in basins between tilted fault blocks (Fig. 319).

Great Salt Lake (Fig. 320) occupies the lowest portion of the surface of a vast block of earth which has been depressed thousands of feet by faulting relative to the adjacent Wasatch Range of Utah. This remarkable lake is described beyond under the caption "Salt Lakes."

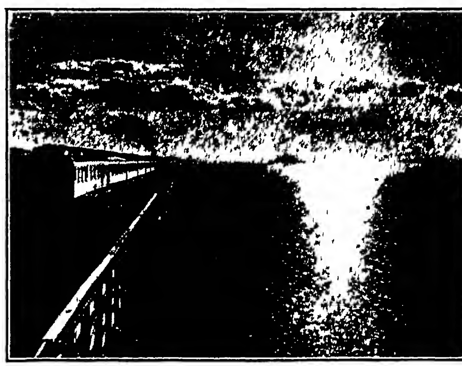

Fig. 320

A view across Great Salt Lake, Utah. (Photo by courtesy of the Southern Pacific Lines.)

In other cases, a block of earth bounded by two normal faults may have been depressed notably between two adjacent land masses, giving rise to a trough-fault basin. An excellent case in point is the basin in the bottom of which lies Lake Tahoe on the California-Nevada line (Fig. 321). The earth block settled several thousand feet to form the basin. The lake is 22 miles long, and 12 miles wide. Its surface lies 6225 feet above sea level. It has a depth of at least 1645 feet, making it one of the few deepest lakes in North America. Its water is remarkably clear and fresh, with an outlet through Truckee River.

A still more remarkable example of a trough-fault basin containing a large lake is the Jordan Valley of Palestine with the

Dead Sea in its lowest portion. The Jordan Valley was formed by the settling of a very long, narrow block of earth thousands of feet between two normal faults. Much of it, including the lake, lies well below sea level. The Dead Sea is described beyond under the caption "Salt Lakes."

Lake basins sometimes come into existence by shifting or settling of earth blocks during earthquake disturbances. Mention has already been made of such a lake in the Owens Valley of California. During the violent earthquake of 1811–1812 in the New

Fig. 321

A view across Lake Tahoe from the Nevada side to California (Photo by courtesy of Tavern Studio, Tahoe, California)

Madrid, Missouri region, a number of lake basins were formed, the largest being occupied by Reelfoot Lake, Tennessee.

By warping. Warping of the earth's crust through differential movement also has caused the development of lake basins. Part of a river valley may be sufficiently upwarped to act as a dam, causing ponding of the water. Among examples ascribed to such a cause are the basin of Lake Geneva in Switzerland, and of Lake Temiskaming in Ontario, Canada. An exceptionally fine, large-scale example caused by warping of a wide area is the great Caspian Sea described beyond under the caption "Salt Lakes."

Among other large lake basins, which at least in part owe their existence to warping, are those of the Great Lakes described beyond.

By simple uplift. When a portion of the sea bottom is raised into land, without faulting or notable warping, there often are shallow, irregular, basinlike depressions filled with water. The water is at first salty, but, in humid climates, it soon gives way

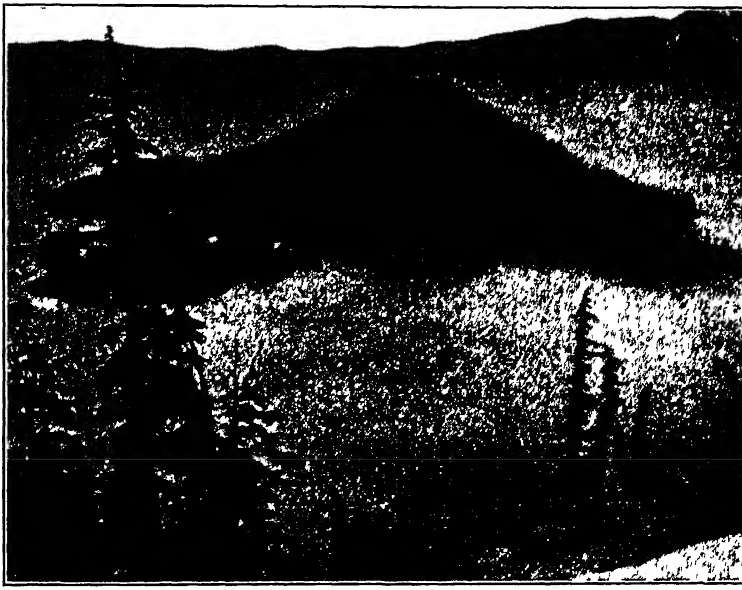

Fig. 322

A view across Crater Lake, Oregon, showing Wizard Island — a recent cinder cone. (Photo by courtesy of the Southern Pacific Lines.)

to fresh water. A number of the lakes of the southern half of Florida, and of the plains of Siberia, are believed to be of this origin. Such lakes are very short-lived, because of their shallowness.

Basins Formed by Vulcanism. — *Crater lakes.* Numerous lake basins are direct results of volcanic activity. Many of them are simply craters of inactive volcanoes more or less filled with water. Sometimes there are groups of such crater lakes, as in the

Auvergne district of France, the Eifel region of Germany, and the vicinity of Rome, Italy. These are all small, but beautiful, lakes.

Many crater lakes also occur in large and small craters of volcanoes in the western United States. Most remarkable of all is Crater Lake in the Cascade Mountains of southern Oregon (Fig. 322). It partly fills a vast hole (caldera), six miles in diameter, which resulted from the collapse and subsidence of the upper portion of a once much higher volcanic cone. The lake is nearly 2000 feet deep, being probably the deepest in North America. Its surface lies nearly 6200 feet above the sea. Great precipitous walls of rock completely encircle the lake. It has no surface outlet, and yet its water is fresh, probably in part because some of its water may leave by underground passages, and in part because no stream flows into it. The water supply is maintained by rainfall and snowfall.

The vast crater pit formed by the terrific explosions of Katmai Volcano, Alaska, in June, 1912, contains a lake of warm water about a mile in diameter.

Lava-dam lakes. Streams of molten lava may flow across valleys and there cool to form natural dams, causing the valley waters to be ponded. Thus a great flow of lava from Skaptar Jókull, Iceland, in 1783, blocked a large river and a number of its tributaries, with resultant development of lakes.

The famous Sea of Galilee in Palestine was formed by a stream of lava which, in very recent geological time, flowed into and across the Jordan Valley, causing the River Jordan to be ponded nearly 700 feet below sea level. The water is fresh because the river flows through the lake.

A number of lava-dam lakes occur in the Sierra Nevada and Cascade Mountains of the western United States. An interesting example is Snag Lake in Lassen Volcanic Park, California, whose water level is held up by the very recent flow of lava already described (p. 314) as partly filling a valley.

Basins Formed by Glacial Action. — *By morainic dams.* Lake basins formed by various processes of glaciation are more abundant than those formed in any other way. Of these, the most numerous by far have resulted from the deposition of glacial débris (moraines) in such manner as to obstruct the drainage of valleys. Many of the 8000 or more lakes in Minnesota, of the thousands in

Wisconsin, and of the thousands in New York and New England belong in this category.

The most common types of morainic dam lakes are finely illustrated in the Adirondack Mountains of northern New York (Fig. 323). Thus the well-known Lake Placid, Saranac Lakes, and Long Lake have their waters ponded by single dams of morainic materials across valleys. They all lie between 1500 and 1900 feet above sea level. The Fulton Chain of eight lakes in the Adirondacks illustrates a series of lakes which occupy basins formed by a succession of morainic dams across a valley.

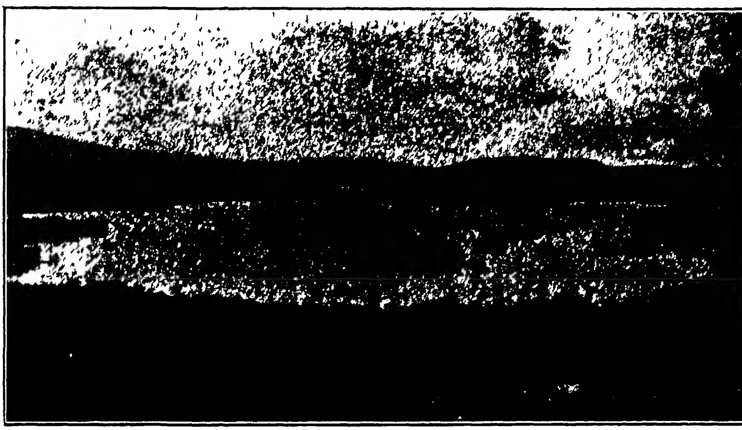

Fig 323

A lake formed by blockading a valley with a morainic dam Blue Mountain Lake, New York (Photo by the author.)

Lake George in the southeastern Adirondacks is a fine example of a large, long, narrow body of water maintained by two morainic dams across a valley, one at each end of the lake. It is 30 miles long, from one to two and one-half miles wide, and lies in a deep, narrow mountain valley.

Lake Chelan in the Cascade Mountains of Washington is, in regard to length, depth, narrowness, and scenic setting, probably the most remarkable mountain lake of the United States (Fig. 324). It is 60 miles long, less than two miles wide, about 1500 feet deep, and set in a winding mountain canyon several thousand feet deep. First a river carved out most of the canyon. Then

great floods of lava dammed its lower end, forming a lake. Finally a great valley glacier plowed through the basin, deepening it, and leaving a heavy morainic accumulation across its lower end, thus still further building up the dam. The present lake water is, therefore, held in place by a combination lava dam and glacial morainic dam.

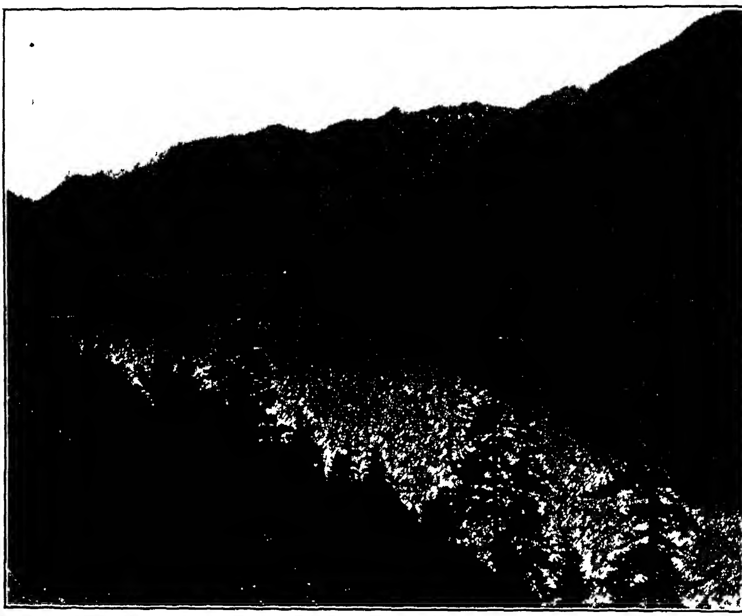

Fig. 324

A view of part of Lake Chelan, Washington, which is in part a lava-dam lake and in part a moraine-dam lake (Photo by courtesy of the U S. Reclamation Service)

The three famous lakes of northern Italy — Como, Garda, and Maggiore — occupy deep, narrow, steep-sided mountain valleys on the southern slope of the Alps. A big glacier flowed down each of these valleys during the Ice Age, and spread out part way upon the Italian plain. Great terminal moraines were formed around the ends of the glacial lobes, and, since the melting of the ice, the moraines have acted as dams across the ends of the mountain valleys, ponding the waters far back in them. Each of these lakes

is over 1000 feet deep. Similar to these Italian lakes in general character, though not so large and deep, but like them in origin, are a number of long, narrow lakes of Glacier Park, Montana.

By ice dams. Glaciers may blockade valleys, and thus cause ponding of waters. Lakes of this kind occur in Greenland, Alaska, and the Alps. An example is a small lake formed where the Great Aletsch Glacier in the Alps slowly flows past the mouth of a tributary valley, causing a ponding of water in the latter. A great glacier flows into the Copper River of Alaska, ponding the water there.

Fig 325

A small moraine-dam lake in the Adirondack Mountains of New York. (Photo by the author.)

Existing ice-dam lakes are not common, and few, if any of them, are large. During the Ice Age, however, thousands of them formed and lasted only as long as the ice dams existed. Some of them were of vast extent, vaster in fact than any existing lakes, with the possible exception of the Caspian Sea. A few large-scale examples will be briefly described.

When the great ice sheet was retreating from northern New York, waters hundreds of feet deep and many miles long were ponded in the Mohawk Valley between the great walls of ice — one in the eastern, and the other in the western, part of the valley. The lake waters lowered as the ice retreated, and they finally drained away completely.

One of the largest of all known ice-dam lakes has been named Lake Agassiz. It occupied the Red River Valley region of Manitoba (including Lake Winnipeg), North Dakota, and Minnesota. It attained a maximum length of about 700 miles, and a width of over 200 miles, when it covered 110,000 square miles, or considerably more territory than all of the Great Lakes. The lake formed because the northward drainage into Hudson Bay was blocked by the front of the retreating ice sheet during a late stage

of the Ice Age. The outlet of this vast lake was southward into the Mississippi.

The Great Lakes constitute the most remarkable chain of big lakes in the world. They cover about 95,000 square miles. Their history is too complicated and eventful to be more than suggested in a very brief account. They did not exist before the Ice Age. Their basins are the results mainly of extensive deposition of morainic materials on their southern sides, and notable down-

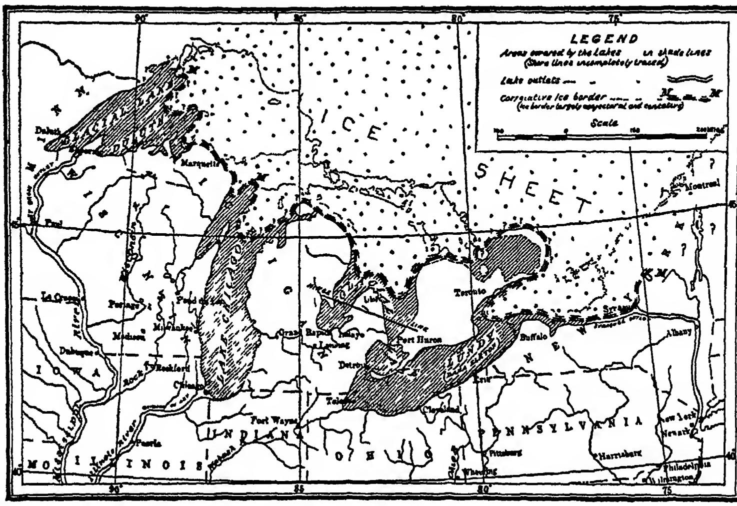

Fig 326

A three-lakes stage of the history of the Great Lakes during the retreat of the great ice sheet (After Taylor and Leverett)

tilting of the land toward the north, during the Ice Age. The broad valleys which formerly occupied the sites of the various basins were also more or less deepened by glacial erosion. Our present interest is, however, a very brief consideration of the wonderful systems of ice-dam lakes which developed during the retreat of the great glacier from the Great Lakes basins. When the front of the ice sheet withdrew far enough northward to free the southern end of the Michigan basin, and the western end of the Erie basin, small glacial lakes developed against the ice walls in those basins. The first-named drained southwestward through the Illinois River, and the other southwestward through the

Wabash River — both into the Mississippi. These lakes enlarged as the ice retreated somewhat farther, and the eastern one drained across Michigan into the western one which, in turn, drained through the Illinois-Mississippi Rivers. At a later stage, when fully half of the Great Lakes basins was freed from the glacier, three large, independent lakes lay against the ice wall (Fig. 326). One of these (Lake Duluth) filled the western half of the Superior basin, with outlet through the St. Croix-Mississippi Rivers.

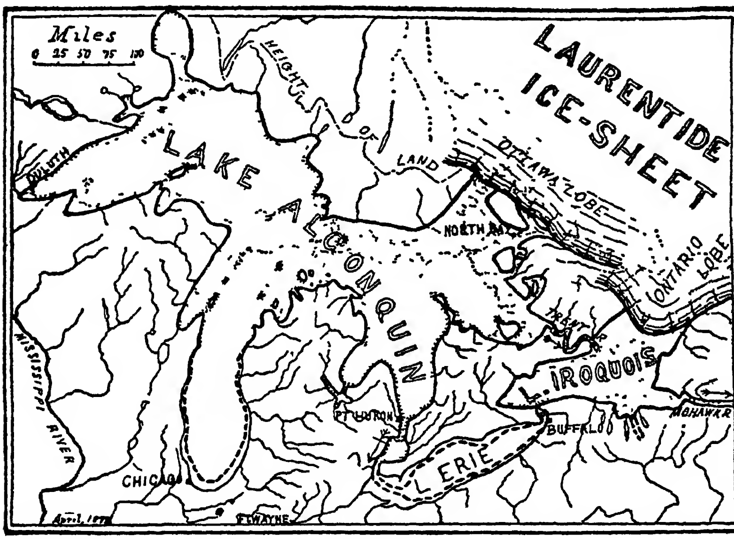

Fig. 327

The Algonquin-Iroquois stage of the Great Lakes history. (After Taylor.)

Another filled most of the Michigan basin, with outlet through the Illinois-Mississippi Rivers. The third lake occupied the Erie basin and the southern end of the Huron basin, with outlet eastward through the Mohawk-Hudson Valleys of New York. During a still later (Algonquin-Iroquois) stage, the Great Lakes assumed nearly their present condition, though they were somewhat larger, and they all drained through the Hudson-Mohawk Valleys of New York because the St. Lawrence Valley was still filled with the glacier (Fig. 327). Finally the ice disappeared from the St. Lawrence Valley, and soon the present-day conditions

obtained. Certain earth-crust movements accompanied the various changes mentioned, so that the Great Lakes basins are also in part of diastrophic origin.

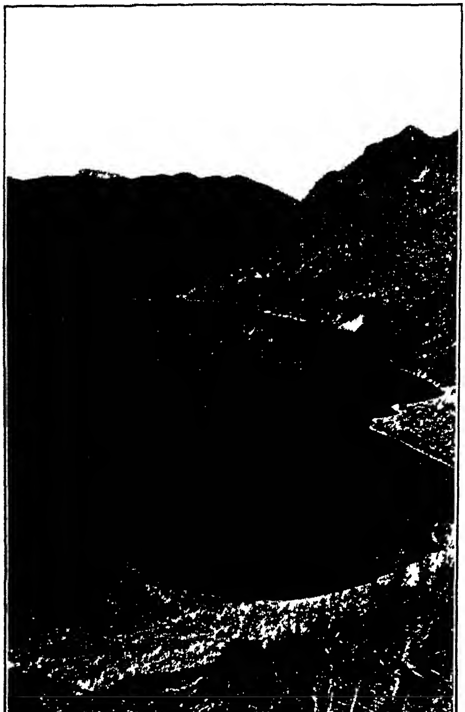

Fig 328
A rock-basin glacial lake. Lake Ellen Wilson, Glacier Park, Montana. (Copyright photo by R E. Marble.)

By glacial erosion. A considerable number of glacial lake basins have been eroded or excavated by the direct action of flowing ice. Small *rock-basin lakes* of this kind, usually not more than ponds, often occur in the bottoms of the cirque basins at the heads of valleys formerly occupied by valley glaciers, because the excavating power of such glaciers was there especially effective. Less often, rock basins have been excavated by glaciers farther down their valleys. Valley-glacier, rock-basin lakes are numerous in parts of the Sierra Nevada, Cascade, and Rocky Mountains (Fig. 328), and also in the high mountains of Europe.

Other rock basins, including some large ones, were produced by the erosive action of the great ice sheets during the Ice Age. Some of the numerous lake basins of Ontario, Canada, quite certainly belong in this category. Ice erosion was especially effective in that region, while glacial deposition predominated from the Great Lakes southward. A large lake recently assigned to this class of rock-basin lakes is Lake Athabaska (area, 2800 square miles) in central-western Canada.

Many glacial lake basins owe their existence to a combination of erosion and deposition. The Great Lakes basins have already been mentioned as belonging in this category. Among many others are the Finger Lakes which form a remarkable group in central-western New York

By irregular deposition of glacial drift. Many ponds and small lakes occupy depressions which have resulted from irregular deposition of glacial débris (drift). Such basins are merely depressions in the surface of the drift. They are common in the upper Mississippi Valley, New York, and New England, especially in association with the many recessional moraines. They differ from typical morainic dam basins not only in that they are completely surrounded by drift, but also in that they very commonly developed on flat, or only slightly hilly, land.

Ponds and small lakes may occupy depressions formed by the melting of large, isolated blocks of ice which have become buried under sediments. Masses of ice detached from a glacier may have been covered by morainic material left by the ice; or such masses may have been buried under material washed from the glacier (as in valley trains and outwash plains), or icebergs stranded in glacial lakes may have been buried under sediments carried into the lakes by streams. Ponds and lakes in such depressions are called *pit or kettle lakes*. They are most strikingly shown on otherwise nearly level, loose, extensive deposits which mark the sites of former glacial lakes. When such a surface is characterized by many kettle holes, some with and some without water, it is called a *pitted plain*.

Basins Formed by Stream Action. — *By flood plain development.* We have already learned (p. 160) that graded and nearly graded rivers tend to wander in meandering loops over their flood plains, and that the necks of such loops are often cut across, leaving *oxbow lakes* like those so wonderfully exhibited on the flood plain of the lower Mississippi River.

Shallow basins often result from uneven deposition of the flood plain sediments, especially in the spaces between the natural levees of the main streams and their tributaries.

By delta growth. As a result of uneven deposition of sediment by the network of distributaries on a delta, certain shallow basins are completely surrounded by the deposits, and thus converted

into so-called *delta lakes*. A fine large-scale example is Lake Pontchartrain in Louisiana.

By alluvial cones. An alluvial cone or fan formed by a tributary stream may be built far enough out into its main stream (or valley) to obstruct the drainage of the latter, causing a ponding of the water. A good case in point is Lake Pepin which lies between Minnesota and Wisconsin. Much sediment carried by the Chippewa River into the Mississippi has there caused a ponding of the latter. Another good illustration is Tulare Lake in the Great Valley of California where the swift King's River, emerging from the high Sierra Nevada Range, has built an extensive alluvial fan into the Great Valley, obstructing its drainage.

By raft blockades. Mention has already been made (p. 196) of stream obstruction and deflection caused by so-called *rafts* or *jams* of trees and logs formed in rivers. The growth of such a raft upstream for many miles in the Red River of Louisiana so obstructed its tributaries as to develop a remarkable series of small and large lakes along them.

By waterfall erosion. Small lakes are sometimes found in abandoned stream courses, particularly where waterfalls have excavated so-called "plunge basins" at their bases. Fine examples of *plunge-basin lakes* are Jamesville Lake near Syracuse, New York, and near Coulee City, Washington, where large rivers once flowed.

Basins Formed in Other Ways. — Brief mention will be made of some of the other modes of origin of lake basins, with examples.

By waves and shore currents. When the mouths of embayments of either sea or lakes are closed by the growth of bars or barriers through the action of either shore currents or waves, or both together (see pages 289, 290), lakes result. Many examples occur along the Atlantic Coast from Long Island southward, and also around the borders of the Great Lakes

By wind. Wind action often piles the materials of bars and barriers higher, thus causing them to be more effective dams where they close embayments of sea or lakes. Wind-blown sand may block streams locally, causing ponding of their waters. This has often happened along the southwestern coast of France. Depressions in sand dune areas sometimes contain water. Wind erosion may, under exceptional conditions, excavate basins in soft rock materials, as in parts of Argentina.

By solution. When sink holes (p 344) are sufficiently obstructed by rock débris at their bottoms they may contain ponds or small lakes. Good examples occur in the northern half of Florida, and in Kentucky.

By landslides. Lakes are sometimes formed where landslides obstruct the drainage in valleys and canyons, particularly in regions of high relief. A good example is in the Kern River Canyon of the southern Sierra Nevada Mountains. In 1892 a great landslide blockaded the upper Ganges River in India, causing a lake five miles long and hundreds of feet deep. The lake disappeared in about two years by a giving way of the dam.

Salt Lakes

Origin of Salt Lakes. — Salt lakes are far less common than fresh lakes. They never have outlets. They almost invariably exist in arid regions, particularly in *interior drainage* regions, like the Great Basin area of the western United States, from which no streams flow into the sea. In such regions the intake (precipitation and inflow) is often not sufficient to cause the lakes to overflow the lowest points of their basins to form outlets. With increase in dryness of climate, a fresh lake may, therefore, become a salt lake because the outlet is sooner or later abandoned, and mineral matter, carried in by streams, steadily accumulates in the water. Great Salt Lake, Utah, is one of the best-known examples belonging in this category. A salt lake may, under certain conditions, become a fresh lake. Thus Lake Champlain, which became detached from the Gulf of St. Lawrence by uplift of the land, was a salt lake at first, but the salt has since been rinsed out through the outlet stream. Such a body of water, which was once connected with the sea, is called a *relic lake.*

Salt lakes may, in short, be formed in two ways, namely, (1) by accumulation of saline matter in lakes with no outlets, and (2) by cutting off arms of the sea either by diastrophism, or by deposition of sediment, particularly in the form of a delta. Examples illustrating these principles will now be briefly described.

Examples of Salt Lakes. — Great Salt Lake, Utah, is a fine example of a salt lake not only whose saline matter has accumulated by concentration through excessive evaporation, but also whose ancestor was a fresh lake. As already mentioned, it occupies

the lowest portion of the surface of a vast down-sunken fault block in the Great Basin region (Fig. 320). It covers nearly 2000 square miles, and its surface lies 4200 feet above sea level. It is remarkably shallow, the greatest depth being only about 40 feet. It is nearly five times as salty as the ocean, that is, it carries about eighteen per cent of saline matter in solution. It contains several billions of tons of common table salt, and hundreds of millions of tons of salts of soda, magnesia, potash, lime, etc. Very briefly stated, the history of the lake is as follows: when the climate was moister, the vast basin, now only partly occupied by the lake, was filled to overflowing with fresh water (Fig. 329). This great lake, called Lake Bonneville, was about two-thirds the size of Lake Superior, and its outlet was northward into the Snake-Columbia Rivers. Lake Bonneville had a maximum depth of over 1000 feet. As the climate became drier, evaporation exceeded intake, and the outlet was abandoned. The water level

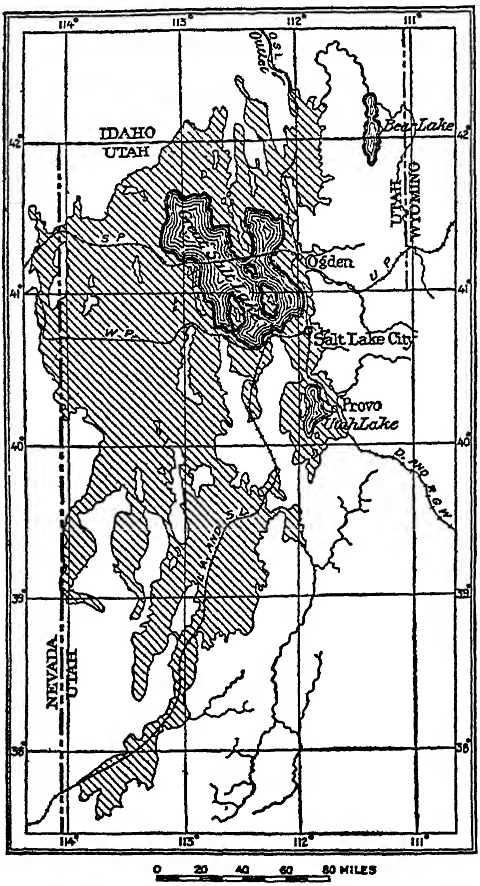

Fig. 329
Map of Great Salt Lake and its vast fresh-water ancestor, called Lake Bonneville (shaded). (After U. S. Geological Survey)

fell, though not uniformly, and the lake became more and more salty by concentration of saline matter carried in by streams. Great Salt Lake is but a shrunken remnant of its vast ancestor. Many shoreline features, such as bars, beaches, deltas, and wave-cut cliffs, marking various levels of the lowering waters of Lake Bonneville, are wonderfully preserved around the sides of the basin (Fig. 330).

Fig. 330
High-level shorelines of Lake Bonneville, Utah. (After Gilbert, U. S. Geological Survey.)

The great Caspian Sea is a fine example of a large arm of the sea cut off by uplift of land. It is hundreds of miles long, and it covers an area larger than the state of California. It lies 85 feet below sea level, and its greatest depth is over 3000 feet. Both the composition of the salts in solution, and the nature of the animal life in its water, point to its former connection with the ocean. The Caspian Sea formerly connected with the Black and Mediterranean Seas across southern Russia, and it was cut off by a broad, gentle upwarp of the land there. A remarkable fact is that this vast body of water with no outlet now contains less salt (less than one per cent) than when it was connected with the ocean. This is owing to the fact that water from the Caspian Sea steadily flows through narrow openings into embayments along its sides, particularly the Gulf of Kara,

Fig 331
Saline deposits at the western end of Baldwin Lake, San Bernardino Mountains, California. (Photo by the author.)

situated where the climate is arid. Great evaporation of the water in the embayments causes the influx of water from the great lake into them. The water of the embayments evaporates, but the salt remains, and even accumulates in beds. Thus the original salt of the Caspian Sea is slowly being removed, and the large quantities of mineral matter brought in yearly by the rivers on the north are not enough to increase the salinity of the lake.

A remarkable case of a large basin cut off from the sea by the growth of a delta is the Imperial Valley — Salton Sink region, containing the Salton Sea in southern California. The Gulf of California once extended about 150 miles farther north. The Colorado River gradually built a great delta completely across the Gulf, thus beheading its northern portion. The beheaded portion was a large lake (area, about 2000 square miles) for a while, but its water slowly evaporated and concentrated, finally leaving only a desert basin mostly below sea level with salt beds in its lowest portion. Between 1904 and 1907, as a result of an accident to the headgate of a great irrigation canal, much of the Colorado River flowed into the basin, and formed the Salton Sea, covering 450 square miles, in its lowest portion. Since 1907 the body of water has diminished in size considerably by evaporation. It now contains approximately one per cent of salts in solution.

The Dead Sea of Palestine lies in the lowest portion of the Jordan Valley which was formed by the sinking of a long, narrow block of the earth's crust between two nearly vertical, parallel faults. It covers an area of about 500 square miles; its greatest depth is about 1300 feet; and its surface lies about 1300 feet below sea level, making it the lowest lake in the world. Approximately 24 per cent of salts, chiefly chloride of magnesia and common salt, are in solution in its water. The Dead Sea is but a remnant of a once much larger (fresh-water) lake which had an outlet to the south. As the climate became drier, excessive evaporation caused the water level to lower more than a thousand feet, that is to the present level of the Dead Sea. The salts in solution have been concentrated from the fresh water brought in by the streams, especially by the Jordan River.

Among other interesting salt lakes, mention may be made of Mono Lake, California, over 6000 feet above the sea, and rich in soda and salt; Owen's Lake, California, nearly 4000 feet above the sea, and very rich in soda; Aral Sea, Siberia, a very large lake

(area, nearly 27,000 square miles) only a little above sea level, and only slightly salty; Lake Van, Armenia, which contains 33 per cent of salts in solution; and Assal Lake in eastern Africa, the surface of whose salt water lies 600 feet below sea level.

Lake Erosion and Deposition

Sea and Lake Erosion and Deposition Compared. — Lake erosion is, in almost every way, like sea erosion, except that the effects produced in lakes are usually less conspicuous because they are smaller, and the waves and undertow, which do nearly all of the erosive work, are less powerful. In large lakes, however, the resulting features of lake erosion, such as wave-cut terraces, cliffs, caves, coves, stacks, and arches, are practically identical with similar features produced by sea erosion (see pages 282–285).

Deposition in lakes is, in many respects, also like deposition in the sea. Thus beaches, barriers, bars, deltas, and wave-built terraces are essentially the same whether formed in sea or lakes. These have all been considered under the caption "Marine Deposits" in Chapter X. There are, however, no deposits in lakes really comparable to deep-sea deposits, with the possible exception of some accumulations of shells of certain tiny plants (diatoms). More or less land-derived sediments carried in by streams accumulate over the entire floors of most lakes. Delta-growth in lakes is particularly strong both because of absence of very appreciable tides, and the usual lack (except in some very large lakes) of very powerful wave and undertow action.

Cycles of shoreline development are also essentially the same for lakes as for the sea (see page 293).

A deposit rather characteristic of some fresh lakes is *marl* which is a light gray mixture of carbonate of lime (often in the form of shells) and clay. It is often in beds 5 to 20 feet thick.

More or less decaying vegetable matter accumulates in many lakes and swamps in humid-climate regions. Such material often forms rather extensive beds of so-called *peat.*

Chemical Deposits in Lakes. — Chemical deposits (various salts) are seldom of importance in fresh lakes. In certain fresh lakes fed by streams rich in dissolved carbonate of iron, the soluble material may, on entering the lakes, become oxidized to the insoluble *limonite* and be deposited on the lake floor. In some

lakes of Sweden there is enough limonite of such origin to be of commercial value as an ore of iron. Carbonate of iron may, under exceptional conditions, precipitate in fresh lakes

The chemical precipitates of lakes are, of all lake deposits, probably the most interesting, characteristic, and important. When, through evaporation, a salt lake shrinks, the minerals in solution become more and more concentrated until deposition of certain of them begins. With continued evaporation to dryness, all minerals in solution are deposited. Some of the most abundant of many minerals contained in the waters of salt lakes are common salt (halite), sulphate of lime (gypsum), sulphate of soda (Glauber Salt), sulphate of magnesia (Epsom Salt), chloride of magnesia, and carbonate of lime (calcite).

The kinds and relative amounts of substances in solution depend largely upon the nature of the rocks surrounding the lake basins because (except in certain relic lakes) they are washed out of those rocks, and carried into the lakes by streams. Thus Great Salt Lake is very rich in common salt because the surrounding rocks are mainly strata of marine origin containing original sea salt. Mono Lake, California, is rich in carbonate of lime and soda because the surrounding rocks are mainly igneous which, on weathering, yield carbonates.

During the dessication of a salt lake, dissolved substances are deposited in the order of their insolubility. Thus if four substances, carbonate of lime, sulphate of lime, common salt, and chloride of magnesia, are in solution, they will precipitate in the order given, the last-named remaining in solution the longest because it is very highly soluble. The entry of flood waters during a rainy season, or a series of rainy seasons, may dilute the water enough to check precipitation of mineral matter from solution, and land-derived sediment will accumulate on the lake floor instead. It is, therefore, readily seen why alternating layers of clay or sand and one or more salts are often found in old lake deposits. Extensive deposits of soda and borax mark the sites of some former lakes, as in parts of Death Valley, and in other basins of southeastern California. Carbonate of lime is now accumulating in Great Salt Lake, and lime deposits of curious shapes and large volume occur in Pyramid Lake, Nevada, and in Mono Lake, California. The extensive salt fields just west of Great Salt Lake were left by the retreating waters of the lake.

Destruction of Lakes

By Filling with Sediments. — This is one of the most important methods of lake destruction. Some one has said that "rivers are the mortal enemies of lakes." All surface waters, especially streams, flowing into lakes carry more or less sediment with them. Most of the sediment accumulates on the floors of the lakes because the latter are such excellent settling basins as already explained (Figs. 332, 333, and 334). Lake basins may, by this process alone, be completely filled, and the lakes destroyed.

Fig. 332
A filled lake basin at an altitude of 9000 feet at Pandor, Colorado (Photo by the author.)

One of the most striking features of the sediment-filling process is delta-growth of the coarser material at the mouths of the tributary streams. As the deltas build out, the lake waters are of course displaced. A few examples may be mentioned. Streams entering the heads of both Seneca and Cayuga Lakes in central-western New York have built delta plains into each about three miles long, and one mile wide. The Rhone River has built a delta 20 miles long into Lake Geneva, one mile of it during the last 1900 years. The city of Interlaken, Switzerland, is built upon a broad delta which has cut in two and partly filled a large lake. Finer sediments are of course more or less distributed over the entire floors of lakes.

Many lakes, particularly those of arid regions, receive more or less wind-blown sediment. In not a few cases extensive accumulations of volcanic dust have formed in lakes.

The materials eroded by waves along lake shores are mostly deposited in the lakes. Although such erosion enlarges the areas of lake basins, nevertheless their waters are, on the average, steadily made shallower because most of the material eroded and deposited comes from well above the lake levels.

By Filling with Organic Remains. — In humid, temperate-climate regions, many small lakes have been, and are being, destroyed by accumulations of vegetable matter, shells, etc. Plants usually grow in great profusion in the shallow, border portions of lakes. As the plants die their remains accumulate to form bogs which, in many cases, have encroached from all sides until lakes have been completely filled. Thousands of old lake bogs occur in New England, Wisconsin, and Minnesota.

Certain plants and animals secrete shells of carbonate of lime, and others, like single-celled diatoms, secrete shells of silica.

Fig. 333
Mountains almost buried under the sediments of former Lake Bonneville, Utah. (After Gilbert, U. S. Geological Survey.)

In many lakes these shells are deposited to such an extent as to appreciably aid in lake-filling.

By Cutting Down Outlets. — The dams of many lakes, particularly those formed of glacial débris, often consist of such loose, incoherent materials that outlet streams readily cut down into them. By this process, a lake surface may be reduced steadily until the lowest level of the lake basin is reached, causing destruction of the lake. Cutting down of outlets has been an important factor in the destruction of many lakes, especially of glacial lakes in regions like New England, New York, Wisconsin, and Minnesota. Of course it should be borne in mind that cutting down of

outlets, filling with sediment, and filling with organic remains may proceed simultaneously.

Where the dams consist of relatively hard rocks, cutting down of outlets proceeds very slowly because outlet streams are usually very clear water whose erosive power is slight. This is true even of large rivers like Niagara and the St. Lawrence which have scarcely lowered the surfaces of the lakes they drain.

By Removal of Ice Dams. — This principle is illustrated in certain regions of existing glaciers, as in the Alps, where a glacier,

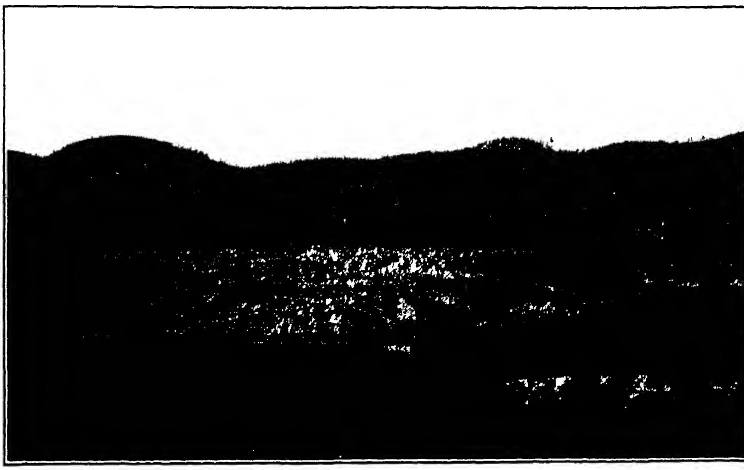

Fig. 334

Glacial lake deposit forming a wide, flat-topped terrace in the upper Hudson Valley near Luzerne, New York. The river is now removing the deposit. (Photo by the author)

causing ponding of water by blockading a tributary valley, may shift position in such a manner as to allow escape of the water either under or alongside the ice.

Many ice-dam lakes, including some of great size, were either completely, or largely destroyed by melting of their dams during the closing stages of the Ice Age. Thus bodies of water covering hundreds of square miles in the Black and Mohawk Valleys of New York disappeared because of the removal of their great ice dams. The once vast Lake Agassiz (already described) was

destroyed in a similar manner, remnants only being left (e.g. Lake Winnipeg).

By Evaporation. — This is a very important method of lake destruction in arid regions where evaporation may exceed intake. Many of the depressions in the Great Basin region which once contained lakes are now dry, or nearly so (e g. Death Valley). Others now contain only small remnants of once large bodies of water, as for example the great basin of Lake Lahontan in western Nevada with its Pyramid Lake.

By Diastrophism. — Ponds and small lakes are sometimes drained through fissures which are formed during earthquake disturbances. Lakes, especially larger ones, may be partly or wholly destroyed by down-warping or down-faulting of their outlet areas, but actual examples seem to be rare. It has been recently advocated that the great postglacial lake which once lay in the Connecticut Valley of New England disappeared by down-warping of its outlet region.

If the southern half of Florida should subside only 20 to 50 feet, most of its numerous lakes would disappear because of flooding of the region by sea water. Submergences of this kind have of course been common during geological time, but it is not easy to point definitely to recent examples of lakes thus destroyed because the evidence is so hidden. Lakes near sea level along sinking coasts are of course doomed to extinction.

Extinct Lakes

We have just explained the most common ways by which lakes are destroyed, and cited some examples. Among the more important criteria by which the sites of former lakes may be recognized are the following: (1) If a lake basin has been completely filled, and since then little affected by erosion, its site is marked by a flat consisting of characteristic lake deposits, practically free from boulders (Figs. 332 and 334). Such deposits may be sediments, organic (bog) materials, or salt-lake mineral deposits.

(2) Basins of larger ponds and lakes, which were not completely filled, very commonly show deposits of coarser sediments, usually in deltas and coalesced deltas, around their borders, and finer sediments, such as clays, farther out. The border deposits rise everywhere uniformly, unless subsequently affected by diastro-

phism, to about the former levels of the standing waters, while the finer sediments lie at various lower levels, depending upon the topography of the lake floors.

(3) In contrast with stream deposits, lake sediments (especially the finer materials) are usually much more uniform in character and structure over wide areas.

(4) In addition to deltas, other shore features, such as wave-cut cliffs, beaches, spits, and bars, are often wonderfully preserved. This is particularly true in arid regions, as around the shores of former Lake Bonneville, Utah (Fig. 330), but they are also often well exhibited in humid regions, as around the shores of the once great Lake Agassiz.

(5) Fossils often prove that deposits were formed in lakes because many forms of life in lake waters are characteristically different from those of sea water.

CHAPTER XV

ECONOMIC GEOLOGY[1]

General Statement

In this chapter it is our purpose to consider briefly geology in some of its direct relations to the arts and industries. When we realize that the value of strictly geological products taken from the earth each year in the United States alone amounts to billions of dollars, we can better appreciate the practical application of geological science. Such products include coal, petroleum, natural gas, many valuable metal-bearing minerals, and many non-metalliferous minerals and rocks. In most cases these valuable products of nature have been slowly accumulated or concentrated at many times and under widely varying conditions throughout the millions of years of known geological time. To trace the extent of, and most advantageously remove, such deposits for the use of man is often impossible unless geological knowledge is brought to bear. Much of the practical application of geology is carried out by the mining engineer who should have, above all, a thorough knowledge of the great principles of geology.

Our plan of discussion is to consider first coal, petroleum, and natural gas; then the most important metalliferous deposits or ores; and finally non-metalliferous minerals and rocks of exceptional commercial importance. Certain useful minerals, and also underground waters, already have been sufficiently discussed from the practical standpoint in Chapters II and XII.

Coal, Petroleum, and Natural Gas

Coal. — Coal is the most valuable of all geological products. Although coal is, strictly speaking, not a mineral, both because of

[1] Much of the material of this chapter is taken by permission from Chapter XXI of the present author's "Geology The Science of the Earth's Crust" which forms volume 3 of Popular Science Library published by P. F. Collier & Son Company.

its organic origin and its lack of definite chemical composition, nevertheless it is generally classed among "mineral resources."

Coal is undoubtedly of organic (plant) origin, as shown by its composition; perfect gradations between plant deposits, like peat, and true coal; and the presence of microscopic plant remains in it. All coal represents plant material which was accumulated in beds analogous to our present-day peat bogs. After a great bed of vegetable matter accumulated it was covered by sedimentary

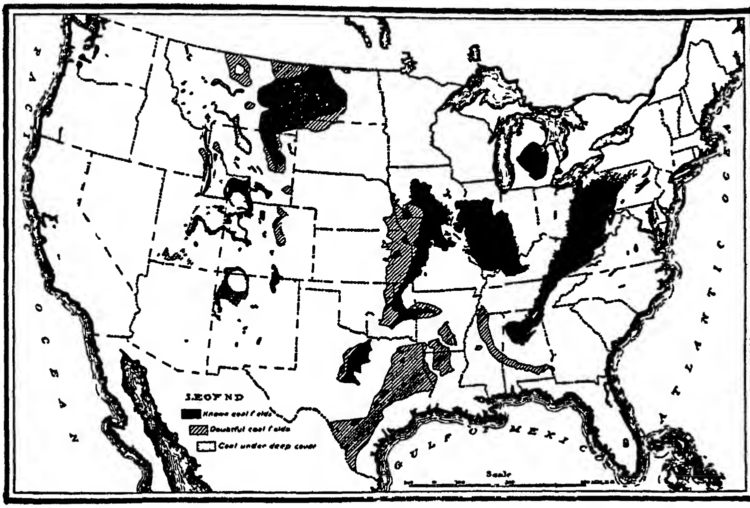

Fig. 335
Map showing the coal fields of the United States.
(After U. S Geological Survey.)

material, and thus buried in the earth's crust. Then, through very slow processes of decomposition, alteration and pressure, the vegetable matter was changed to coal. Anthracite represents the greatest degree of change in the vegetable matter.

The most perfect conditions for prolific plant growth and accumulation as great beds in the earth's crust were during the Pennsylvanian period of the late Paleozoic era in many parts of the world, but especially in the United States, China, Great Britain, and Germany. Most of the world's great supply of coal by far comes from rocks of Pennsylvanian age; next in importance

are Cretaceous rocks; and some comes from strata of other ages later than the Pennsylvanian, even as late as the Tertiary.

The United States not only has the greatest known coal fields, but also it produces far more coal than any other country. In 1918 the production was 678,000,000 short tons, the greatest in the history of the country. In 1925 the production was 585,000,000 tons. Is there real danger that our supply of coal will soon run out? Hardly so, when we consider, first, the fact

Fig. 336
An outcropping coal bed 13 feet thick, in Montana. (Photo by Campbell, U. S. Geological Survey)

that probably not more than one per cent of the readily available coal has thus far been removed, and, second, the high probability that the average rate of increase in coal production for the last twenty years will not continue. In the case of the very restricted anthracite coal fields, what might be called a crisis has already been reached, because a very considerable part of the available supply has been taken out.

Approximately 350,000 square miles of the United States are underlain with one or more beds of workable coal (not including

lignite) — in some areas 5 to 20 or more beds one above the other. There are also about 150,000 square miles of country underlain with the more or less imperfect coal called *lignite*. Map Figure 335 shows the principal coal fields of the United States.

The greatest production of coal by far is from the Appalachian Mountain district, extending from Pennsylvania to Alabama, where nearly all the coal is bituminous of Pennsylvanian age. There, as well as elsewhere, the coal beds are interstratified with various kinds of sedimentary rocks, most commonly with shales and sandstones. In the Appalachian field the strata including coal beds are more or less folded toward the east, and they are nearly horizontal toward the west.

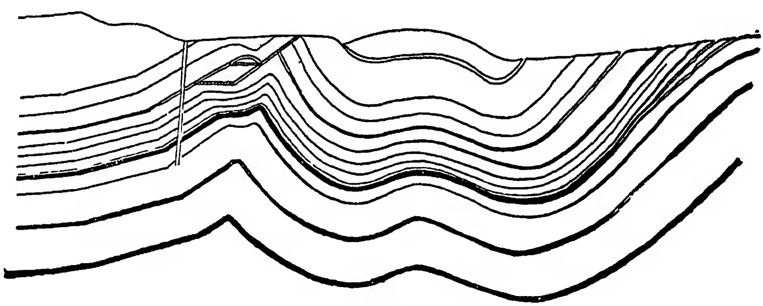

Fig. 337

Structure section more than 1000 feet deep showing folded anthracite beds of Pennsylvania. (After U. S. Geological Survey)

The greatest production of anthracite coal by far is from central-eastern Pennsylvania where strata of Pennsylvanian age, including a number of anthracite beds, are more or less highly folded (Fig. 337). Less than 500 square miles are there underlain by workable anthracite coal.

Next to the greatest production of coal in the United States is from the two large areas in the middle of the Mississippi Valley (Fig. 335). It is all bituminous coal associated with nearly horizontal strata of Pennsylvanian age.

The scattering areas through the Rocky Mountains yield all types of coal — anthracite, bituminous, and lignite. In some of these areas the coal beds have been but little disturbed from their original horizontal position, but usually they are more or less

folded along with the enclosing strata, the crustal disturbances affecting the coal beds having taken place late in the Mesozoic era and early in the Cenozoic era. Practically all of these coals are of Cretaceous and Tertiary ages, the best being Cretaceous. Very little of the Rocky Mountain coal is anthracite.

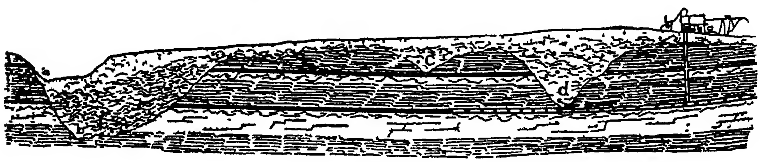

Fig. 338

Nearly horizontal coal beds in Indiana, with outcrops mostly concealed by glacial drift (After G. H. Ashley)

On the Pacific Coast, coal production is relatively very small. The coals are there bituminous to lignitic of Tertiary age, usually folded in with the strata.

In Alaska there are widely distributed, relatively small, coal fields, but they have been little developed. Alaskan coals range in age from Pennsylvanian to Tertiary, and in kind from anthracite to lignite.

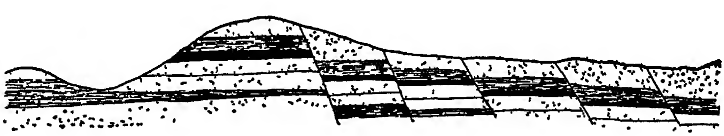

Fig 339

Step-faulted coal beds in Scotland. (After J. C Branner.)

Petroleum. — Crude oil or petroleum is an organic substance consisting of a mixture of hydrocarbons, that is, it is made up very largely of the two chemical elements carbon and hydrogen in rather complex and variable combinations. It is practically certain that petroleum has been derived by a sort of slow process of distillation from organic matter — animal or vegetable, or both — in stratified rocks within the earth. Many strata, as for example carbonaceous shales, are more or less charged with dark-colored, decomposing, organic matter. The chemical composition itself, the kinds of rocks with which it is associated, and certain

optical (microscopic) tests all point to the organic origin of petroleum. In southern California certain of the oils have quite certainly been derived from very tiny oily plants, called *diatoms*, which fill many of the strata.

During the last twenty years petroleum has come to be one of the most important and useful natural products. Among the many substances artificially derived from petroleum are kerosene, gasoline, naptha, benzine, vaseline, and paraffine. The United

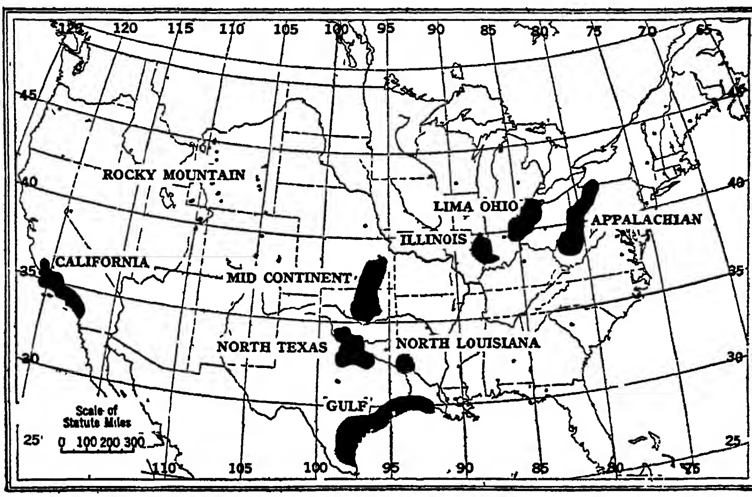

Fig. 340

Map showing the principal oil-bearing regions of the United States. (After Geological Survey of Kansas)

States greatly leads in the production of petroleum, while Mexico and southern Russia are important producers. Map Figure 340 shows the chief oil fields of the United States, the principal areas underlain with petroleum-bearing strata being the northern Appalachian field (through western Pennsylvania to central West Virginia); the Ohio-Indiana field (central Indiana to northwestern Ohio); the mid-continental field (southeastern Kansas, northeastern Oklahoma, and northeastern Texas); the southeastern Texas-Louisiana field; and the southern California field. The areas now known to be underlain with oil total about 10,000 square miles.

In the Appalachian, Ohio-Indiana, and mid-continental fields the strata carrying oil range in age from Ordovician to Pennsylvanian, and they are mostly but little disturbed from their original horizontal position. The Texas-Louisiana oils come mainly from Cretaceous and Tertiary strata with a gentle downtilt under the Coastal plain toward the Gulf. In California the oil-bearing strata are of Tertiary age, and they have been generally much disturbed and folded.

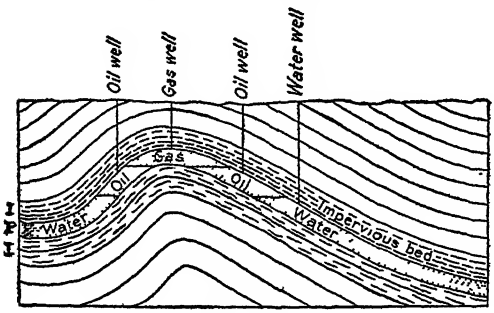

Fig 341

Structure section illustrating a very common mode of occurrence of oil (After U S. Geological Survey)

Under proper conditions below the earth's surface, the derived oil accumulates in porous or fractured rocks. There must of course be a source from which the petroleum is derived or distilled; a porous or fractured rock formation to take it up; a cap-rock or impervious layer to hold it in; and a proper geologic structure to favor accumulation. The most common porous (containing) rock is sandstone, and the most common cap-rock is shale. "Oil is rarely found without gas, and saline water is likewise often present. If the containing strata are horizontal, the oil and gas are usually irregularly scattered, but if tilted or folded,

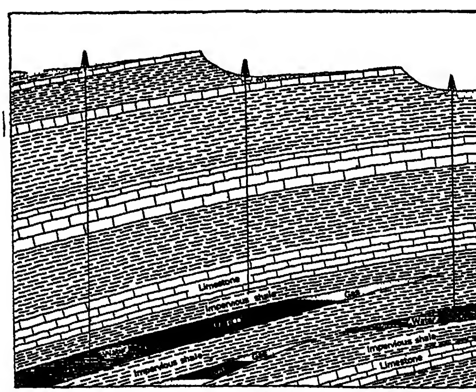

Fig 342

Structure section illustrating a common mode of occurrence of oil (After Geological Survey of Kansas.)

and the beds porous throughout, they appear to collect at the highest point possible. It was the result of observations along this line that led I. C. White to develop what is known as the 'anticlinal theory.' According to this theory, in folded areas the gas collects at the summit of the fold (anticline), with the oil immediately below, on either side, followed by the water (Fig. 341). It is of course necessary that the oil-bearing stratum shall be capped by a practically impervious one. If the rocks are dry, then the chief points of accumulation of the oil will be at or near the bottom of the syncline (downfold) or lowest portion of the porous bed If the rocks are partially saturated with water, then the oil accumulates at the upper level of saturation. In a tilted bed, which is locally porous (Fig. 342), and not so throughout, the oil, gas, and water may arrange themselves according to their gravity in this porous part" (H. Ries).

Fig. 343

An oil gusher in the Sunset-Midway district, California, in 1910. (Photo by R. W. Pack, U. S. Geological Survey.)

Although the term "oil-pool" is commonly used, there is really no actual pool or underground lake of oil, but rather there is porous rock saturated with oil. Sometimes the oil is under great pressure (either gas or hydrostatic pressure) and the oil shoots into the air, forming a gusher (Fig. 343), when a well taps an "oil-pool." It has been estimated that, in an oil field of average productiveness, a cubic foot of the porous rock contains from 6 to 12 pints of oil. The life of a well drilled into an "oil-pool" varies from a few months to 20 or 30 years, or sometimes even more. A heavy producer (especially a gusher) almost invariably falls off in production notably in a few months, or at most in a few years.

The world's output of petroleum for 1925 was 1,000,000,000 barrels, of which the United States produced 756,000,000 barrels,

soft high grade ore is removed by steam shovels in great open pits (Fig. 344). In the several districts of northern Michigan and Wisconsin, the ores (nearly all hematite) are associated with more or less highly folded rocks at considerable depths. The Lake Superior iron ores all occur in rocks of Archeozoic and Proterozoic ages. According to the best explanation of their origin, the iron of the ores was once part of a sedimentary series of rocks in the form of iron carbonate and silicate interstratified with layers of a flintlike rock, and associated with slate, quartzite, etc. After these rocks were raised into land and subjected to weathering, the old iron compounds were altered to oxides, mainly hematite, and somewhat concentrated. Further concentration of the ore was caused by dissolving out the flintlike layers of the old rocks (Fig. 345).

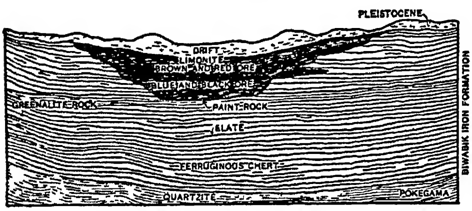

Fig. 345

Structure section showing the mode of occurrence of hematite ore at Mesabi, Minnesota (After Leith, U. S. Geological Survey)

The Birmingham, Alabama, region is the second most important iron ore producer in the United States. The ore is hematite, forming part of a Silurian formation. The ore appears to be an original bed (or locally several beds) of fairly rich iron ore which was deposited on the shallow Silurian sea-bottom, and then covered by other strata. At the close of the Paleozoic era the iron ore was more or less highly folded in with other strata throughout the Appalachians. A remarkable fact regarding the Birmingham district is that, in the near vicinity of the ore, there are both coal for fuel and limestone flux for smelting the ores.

The next most important iron-mining district of the United States is the Adirondack Mountain region of northern New York. Magnetite is the ore (Fig. 346), and it occurs in more or less irregular lenses and bands in granite and other closely associated rocks of pre-Paleozoic age. One view regarding the origin of this ore is that it segregated during the process of cooling of the molten granite, and another view (recently advocated by the author) is that it was derived from an older iron-rich igneous formation

either by the molten granite, or by very hot solutions from it, and concentrated into the ores.

The third important iron ore is limonite. Most of it, in the United States, comes from the Appalachian Mountains. It is all of secondary origin, that is, it has been derived from certain early Paleozoic iron-bearing limestones either by weathering or solution, and concentrated into ore deposits.

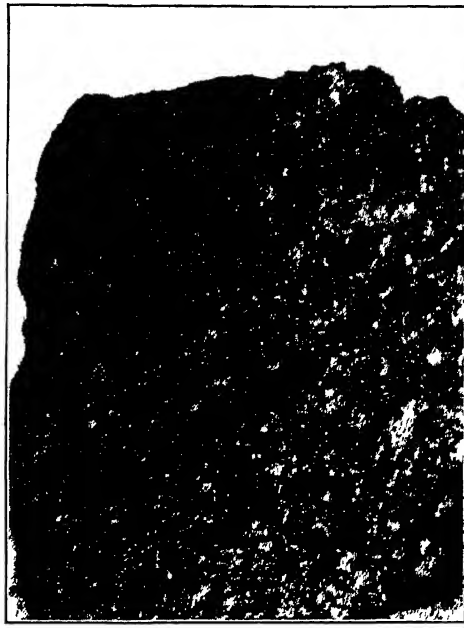

Fig. 346

A specimen of magnetic iron-ore from Lyon Mountain, New York. (Photo by the author.)

Copper. — This is one of the most useful of all metals. Various minerals containing copper are found in many parts of the world, but only about six of them are really important as ores. These are native copper, chalcopyrite, chalcocite, azurite, malachite, and cuprite, most of which are described in Chapter II. The number of places where they may be profitably mined as ore is distinctly limited. Fifteen or twenty countries produce more or less copper, but the United States is by far the greatest producer. The output was nearly 2,000,000,000 pounds in 1916, and 1,700,000,000 pounds in 1925. The other leading producers are Japan, Chile, Mexico, Spain, and Canada. The principal producing states are Arizona, Montana, Michigan, and Utah.

In Arizona several great copper mining districts lie in the southeastern one-fourth of the state. Almost invariably the ores are directly associated with limestone and an igneous rock (gran-

ite), both of late Paleozoic age (Fig. 347). The ores are almost always near the border between the two rocks, mostly as great irregular deposits within the limestone, and less commonly as veins within the granite. The original ores were carried in solution and deposited by hot liquids (or vapors) from the cooling granite.

In the region around Butte, Montana, most of the ores are sulphides of copper (mainly chalcocite) which occur with quartz in a great system of nearly parallel veins in granite of Tertiary age. "It is supposed that in the copper veins the hot ore-bearing solutions ascended the fractures in the (hot) granite, replacing the rock by ore, and resulting in an intense alteration of the walls."

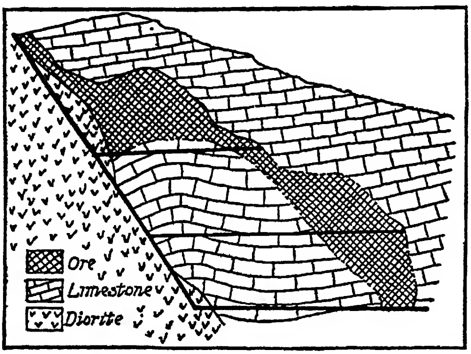

Fig 347
Structure section showing the mode of occurrence of copper ore at Globe, Arizona. (After Wendt.)

In Michigan the mines are located on Keweenaw peninsula which extends into Lake Superior. A unique feature is that the ore is native copper associated with some native silver. The rocks containing the ore are steeply tilted lava sheets and conglomerate strata of Proterozoic age. Openings in porous lava and spaces between the conglomerate pebbles have been filled by metallic copper which was carried off in hot solutions from the cooling lavas. Certain of the mining shafts have been sunk more than 5000 feet below the surface, these being among the deepest in the world.

In Utah the greatest mining district is at Bingham Canyon, southwest of Salt Lake City. The rocks are late Paleozoic strata pierced by a large body of igneous rock. Some of the sulphide ores (mainly chalcopyrite) occur in veins in the igneous rock, and some in large tabular masses in the adjacent limestone. Hot solutions from lower portions of the uncooled igneous rock carried

the ore in solution into the limestone, and also into cracks in the upper cooled igneous rock.

Lead. — Lead must surely be counted among the five or six most useful metals. As in the case of nearly all of the other most important natural resources, so the United States is the world's greatest producer of lead. The output of lead in 1916 was 552,000 short tons, and 655,000 tons in 1925. Most of it came from Missouri, Idaho, Utah, and Colorado. The leading other countries are in order Spain, Germany, Mexico, and Australia. Nearly all the lead comes from the mineral galena (a sulphide of lead) which is described in Chapter II.

The greatest lead-mining district is in the vicinity of Joplin, Missouri, where the ore (galena), associated with much zinc ore, occurs as veins and great irregular deposits in limestone of early Paleozoic age. It is generally agreed that underground waters dissolved the ores out of the limestone in which they were disseminated as tiny particles and deposited them in concentrated form at lower levels.

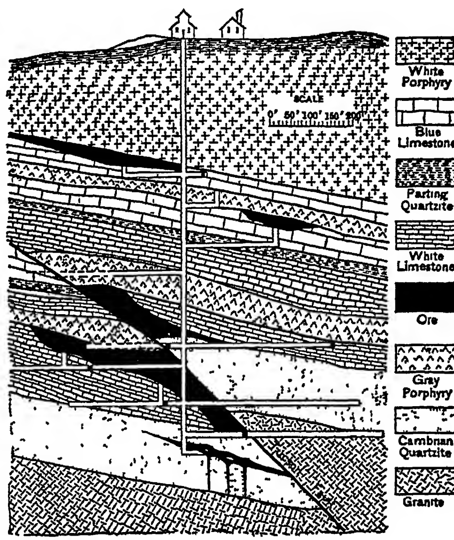

Fig. 348

Structure section showing the mode of occurrence of lead and zinc ores at the Tucson Shaft, Leadville, Colorado. (After Argall)

In the famous Coeur d'Alene district of northern Idaho the great output of lead is obtained from a lead-silver ore, that is galena rich in silver. It occurs in great fissure veins mostly following fault fractures in highly folded strata of Proterozoic age. Igneous rocks cut through the strata, and it is believed that hot ore-bearing solutions given off from the highly heated igneous rocks rose in the fissures and deposited the ores.

The Park City and Tintic districts of Utah are great producers of lead. The lead ore (galena) is usually rich in silver. It occurs mainly in veins and irregular deposits in limestone of Paleozoic age closely associated with certain igneous rocks.

One of the most famous mining districts in the world is that around Leadville, Colorado, where ores of four metals — gold, silver, lead, and zinc — have been extensively mined. The salient points in the rather complex geology are the following: Paleozoic strata, including much limestone, rest upon a foundation of pre-Paleozoic granite. Sheets of igneous rock are interbedded with the strata, and many dikes of igneous rocks cut through the whole combination. After the last igneous activity, all the rocks were somewhat folded, and notably faulted in many places. The ores were dissolved out of the igneous rocks and deposited in large masses mostly in the limestone, and in fissure veins especially along and near the fault zones (Fig. 348).

Zinc. — Another of the few most useful metals is zinc. It never occurs in metallic form in nature, but most of it by far is obtained from the ore-mineral sphalerite, described in Chapter II. A red oxide of zinc ore, called *zincite*, assumes great economic importance in New Jersey.

In 1917 the United States produced 686,000 short tons of zinc. In 1925 the production was 590,000 tons. The United States is the world's greatest producer. The four leading producing states are Missouri, Montana, New Jersey, and Colorado. Germany and Belgium are the greatest foreign producers.

Most important of all in the United States is the district around Joplin, Missouri, where the ore is closely associated with lead ore. The mode of occurrence and origin of these ores are above referred to in the discussion of lead.

In the Butte, Montana, region, some of the great east-west fissure veins in granite are rich in silver ores in the upper levels, and in zinc ores (mainly sphalerite) at depths of from some hundreds of feet to nearly 2000 feet, that is, as far down as they have been mined. They, like the great copper veins of the same general district, were carried by hot solutions which rose from the lower still very hot granite, and deposited the ores in fissures of the same cooler rock higher up.

In the general vicinity of Franklin, New Jersey, the zincite ore-deposits occur in white limestone along, or close to its contact

with, metamorphosed (altered) strata and granite of early Paleozoic age. It is not definitely known how the ore originated, but it was probably derived in solution from the hot granite, and deposited in the limestone by replacement of the latter.

In Colorado the principal zinc mines are around Leadville where lead ore is nearly always directly associated with the zinc ore. This district is above described in the discussion of lead.

Gold. — This precious metal has been used and highly prized by man for thousands of years. The Transvaal region of South Africa has for two decades been the world's greatest gold producer. In 1925 the Transvaal region produced gold to the value of nearly $200,000,000; the United States about $50,000,000; Canada about $36,000,000; Mexico, $16,000,000; and Australia and New Zealand, $14,000,000. In 1916 the gold production of the United States was over $90,000,000.

Most of the commercially valuable gold occurs in nature as native gold either mixed with gravel and sand (i.e. placer deposits) along existing or ancient stream beds, or in veins mechanically held in the mineral pyrite (described in Chapter II) in submicroscopic form, or mixed with quartz in vein deposits. In deep vein deposits it is quite the rule to find free (or native) gold mechanically and visibly mixed with quartz in the upper levels, while deeper down the gold is mechanically, but invisibly, held in combination usually in pyrite, which latter is associated with quartz. This difference is due to the fact that the lower-level ores are now just as they were formed, but in the upper levels the ores have been weathered and the gold set free and often more or less further concentrated by solutions. Vein deposits are found in many kinds of rocks — igneous, sedimentary, and metamorphic — of nearly all ages, though they are generally directly associated with igneous rocks. In nearly all cases the best evidence indicates that the vein fillings were formed by hot ore-bearing solutions from the igneous rocks which deposited the ore plus quartz in fissures in either the igneous rocks, or adjacent rocks. Among the many localities where fissure veins of the kind just described are of great economic importance are the "Mother Lode" belt of the Sierra Nevada Mountains of California; Cripple Creek, Georgetown, and the San Juan region of Colorado; and Goldfield, Tonopah, Bull Frog (Fig. 349), and Comstock Lode of Nevada.

Placer deposits, that is, free gold mixed with gravel and sand,

also yield much gold. They are most prominently developed in California and Alaska. These gold-bearing "gravels represent the more resistant products of weathering, such as quartz and native gold, which have been washed down from the hills on whose slopes the gold-bearing quartz veins outcrop, and were too heavy to be carried any distance, unless the grade was steep. They have consequently settled down in the stream channels, the gold, on account of its higher specific gravity, collecting

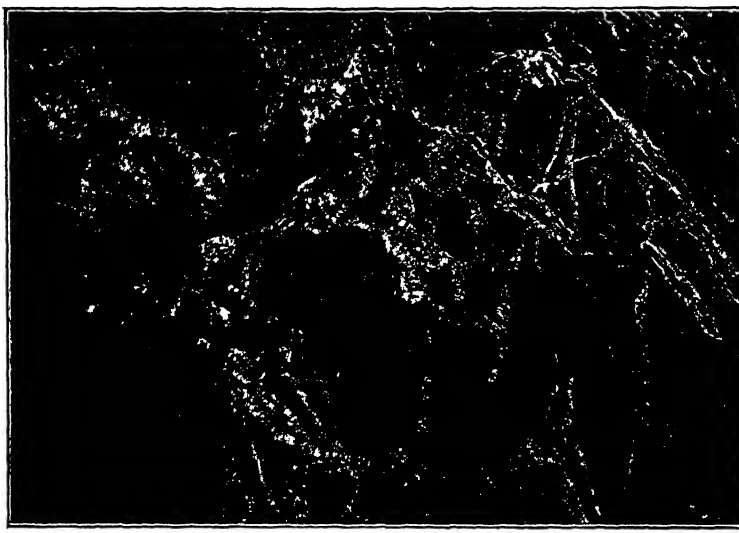

Fig. 349
Gold-bearing quartz veins in Bullfrog Mine, Rhyolite, Nevada. (After F. L. Ransome, U. S. Geological Survey)

usually in the lower part of the gravel (placer) deposit" (Ries). Such gold occurs as grains, flakes, or nuggets.

Most of the gold of South Africa comes from the Witwatersrand district where the native metal occurs in a unique manner in beds or layers of conglomerate associated with other strata, all the rocks being considerably folded and somewhat faulted. Some of the mines are several thousand feet deep. The gold either accumulated in placer form with gravel which later consolidated into conglomerate, or it was introduced into spaces between the pebbles subsequently by ore-bearing solutions.

Silver. — For many years the United States and Mexico have been the world's greatest silver producers, sometimes one and sometimes the other leading, with Canada third, and Australia fourth. In 1925 the production of silver in Mexico was $65,000,000 and in the United States $46,000,000 In the United States the chief producing states are Montana, Utah, Idaho, and Nevada.

In Montana most of the silver is in the native form, more especially in the upper portions of the great veins rich in copper and zinc ores near Butte. These ores and their origin are described above under the captions "Copper" and "Zinc."

The two greatest silver districts of Nevada are Tonopah and Comstock Lode where silver and gold minerals are associated as ores in Tertiary igneous rocks, the ores having been deposited in veins by hot ore-bearing solutions from the igneous rocks.

In Idaho the Coeur d'Alene district produces most of the silver, the ore there being a silver-bearing lead ore (galena). The nature and origin of these deposits are described above under the caption "Lead."

In Utah the silver is also obtained from silver-bearing galena especially in the Tintic, Cottonwood Canyon, and Bingham Canyon districts where the ores occur mainly as irregular deposits and in fissure veins in Paleozoic strata (chiefly limestone) directly associated with igneous rocks, hot ore-bearing solutions from the igneous rocks having furnished the ores.

Tin. — Production of tin in the United States has never amounted to much, a little mining having been carried on from time to time in South Carolina, Black Hills of South Dakota, and southern California. About one-third of the world's supply of tin (143,000 long tons in 1925) comes from the Malay Peninsula and two small islands near by. The only other great producer is Bolivia, though a number of other countries produce considerable amounts.

The only important ore of tin is the mineral cassiterite, described in Chapter II. In the Malay region the ore all occurs in placer deposits and is, therefore, of secondary origin, the source of the ore not being known. In Bolivia the tin ore occurs in veins in, and close to, granite, the ore having been carried by very hot vapors or liquids which were derived from the still highly heated granite.

Aluminum. — The mineral called bauxite (a hydrous oxide of

aluminum) is the great ore from which aluminum is obtained by an electrical process. Bauxite is non-crystalline, relatively light in weight, white to yellowish in color, and in the form of rounded grains, or earthy or claylike masses. The United States and France are the only two great producers of bauxite, most of which is treated for metallic aluminum. In the United States the principal deposits are in Georgia, Alabama, and Arkansas. Bauxite is probably always a secondary mineral formed by decomposition of igneous rocks rich in certain aluminum silicate minerals. In some cases, as in the Georgia-Alabama region, the bauxite appears to have been formed and concentrated in deposits by hot solutions from uncooled igneous rocks.

Mercury. — This metal, commonly known as "quicksilver," is of special interest because it is the only one which exists in liquid form at ordinary temperatures. The metal occurs in only small quantities in nature, most of it by far being obtained from the red mineral called cinnabar, described in Chapter II.

The greatest quicksilver producing countries are Italy, Spain and the United States In the United States, California is by far the leading state, while Texas and Nevada are the only other important producers.

In California most of the ore occurs in veins and irregular deposits in metamorphosed strata of Mesozoic and Cenozoic ages usually closely associated with igneous rocks. There, as well as in other parts of the world, hot vapors from igneous rocks carried the volatile ore upward and deposited it in fissures.

Other Economic Products

Building Stones. — Some of the principal features which should be considered in regard to building stones are power to resist weathering; power to withstand heat; color; hardness and density; and crushing strength. Building stones representing rocks of nearly all important geologic ages are widely distributed throughout the world.

Granite, including certain other closely related rocks, is one of the oldest and most useful building stones. The New England states are the greatest producers, while the Piedmont Plateau district (east of the Appalachians) from Philadelphia to Alabama also contains important granite quarries. In the Adirondack

Mountains, in Wisconsin and Minnesota, through the Rocky Mountains, and in the Sierra Nevada Mountains there are extensive areas of granite which are relatively little quarried. The granite usually occurs in regions of highly disturbed rocks where great volumes of the molten material were forced into the earth's crust, cooled, and later laid bare by erosion.

Marble, according to the geological definition, is a metamorphosed limestone, that is a crystalline limestone. More loosely

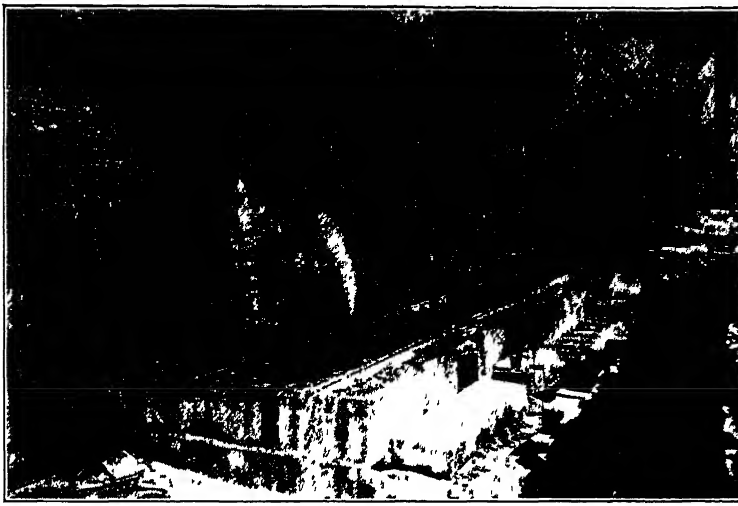

Fig. 350

A limestone quarry for building stone. Bedford, Indiana. (Photo by courtesy of the Bedford Quarries Company.)

in trade, any limestone which takes a polish may be called marble. The greatest marble-producing districts of the United States are western New England (especially Vermont), the Piedmont Plateau, and Appalachian Mountains, all in rocks of Paleozoic age. In northern New York and in the mountains of the west there are relatively few marble quarries.

Ordinary *limestones* are widely distributed in many states where they range in age from early Paleozoic to Tertiary. Most of the quarries supply stone for near by markets. The so-called Bedford limestone of Indiana has, for many years, been a widely

used limestone for building purposes in the United States (Fig. 350).

Sandstones, which are stratified rocks consisting mainly of rounded quartz grains cemented together, are widely used in building operations. Like limestones, they are very widespread in formations of all ages except the very oldest. There are many sandstone quarries supplying more or less local markets throughout the country. Two of the best known and most widely used

Fig 351

A roofing slate quarry. Brownsville, Maine. (After T N Dale, U S. Geological Survey.)

sandstones are the so-called brownstone of Triassic age extending interruptedly from the Connecticut Valley of Massachusetts to North Carolina, and the Berea, Ohio, sandstone of light gray color and uniform texture.

Slate is mostly a metamorphosed shale, that is, a shale which has been subjected to great pressure within the earth so that the stratification has been obliterated, and a well defined cleavage has been developed at right angles to the direction of application of the pressure. Good slate is fine grained, dense, and splits readily into wide, thin plates. It occurs only where mountain-

making pressure and metamorphism have been brought to bear upon the strata. Most of our great slate quarries are located in early Paleozoic rocks of New England (Fig. 351), eastern New York, and southward through the Piedmont Plateau. Some quarries are also located in Arkansas, Minnesota, and California.

Clay. — Most clays originate by the weathering of rocks, particularly igneous and metamorphic rocks rich in the mineral feldspar. As a result of the decomposition of the feldspar, much clay is formed, the main substance of which is kaolin. Both feldspar and kaolin are described in Chapter II. When the resulting clay rests upon the rock from which it has been derived it is called residual clay. Much of the clay is, however, carried away, mainly by streams, and deposited in lakes or the sea, or on river flood-plains. Some clay deposits are of wind-blown origin, and still others are formed by the grinding action of glaciers. Clays are very widespread, and they are directly associated with rocks of all geologic ages.

Lime and Cement. — Limestone, which is one of the most common and widespread of all stratified rocks, forms the basis for the manufacture of the important substances *lime* (or " quick-lime ") and *Portland cement.* Lime results when pure limestone (carbonate of lime) is " burned " or heated to a temperature high enough to drive off the carbonic acid gas.

Certain limestones containing clay of the right kind and proportion are called *natural cement rocks* because, after being " burned," they develop the property of " setting " like cement when mixed with water. The " setting " of a cement is due to the fact that certain chemical compounds formed during the heating, crystallize when mixed with water, and the hard, tiny interlocking crystals of the newly formed silicate minerals give rigidity to the mass. Of recent years Portland cement has largely superseded the natural rock cements. " Portland cement is the product obtained by burning a finely ground artificial mixture consisting essentially of lime, silica, alumina, and some iron oxide, these substances being present in certain definite proportions " (Ries). The necessary ingredients are generally obtained by grinding and burning carefully selected mixtures of limestone in some form with clay or shale.

Salt. — Most of the common salt (the mineral *halite*) of commercial value occurs in nature in sea or salt-lake water; or

in beds of *rock salt* associated with other strata; or as *natural brine* in openings or pores in certain rocks. Considerable salt is obtained by evaporation of tide water, as around San Francisco Bay, and of salt-lake water, as at Great Salt Lake, Utah. The salt of a salt lake has been washed out of the rocks of the surrounding country, and gradually accumulated in the lake because it has no outlet.

Most important of all sources of salt is the rock salt which occurs in the form of strata within the earth's crust. Such strata are found in rocks of nearly all ages from the early Paleozoic to the present. They have resulted from the evaporation of salt lakes or salty, more or less cut-off, arms of the sea, after which other strata have accumulated on top of them. Thus in the Silurian system of nearly horizontal strata underlying all of southwestern New York state there occur, almost universally from one to seven beds of salt. At Ithaca, New York, seven salt beds were struck in a well at a depth of about 2200 feet. One well in central-western New York penetrated a layer of solid salt 325 feet thick. Some of this New York salt is being mined much like coal, but most of it is obtained by running water into deep wells to dissolve the salt, the resulting brine being pumped out and evaporated.

Under portions of southern Michigan, salt occurs both in beds and in natural brines charging certain porous rock layers Both the salt beds (of Silurian age) and the brines (of Mississippian age) supply great quantities of salt. The brines are pumped out and evaporated.

In 1925 the United States produced 7,400,000 short tons of salt Michigan and New York are the leading producers, followed by Kansas, Ohio, West Virginia, and California.

Gypsum. — The composition and properties of this common and useful mineral are given in Chapter II. *Rock gypsum* is the variety of great commercial importance. It is widespread, being quarried in many states, and occurs interstratified with rocks of many ages where it has originated by evaporation, or partial evaporation, of salt-water lakes, or more or less cut-off arms of the sea. Salt beds are often associated with gypsum.

For about ten years (including 1925) the average yearly production of gypsum in the United States has been several million long tons, or about eight times that of Canada, the nearest com-

petitor. New York, Iowa, Michigan, and Ohio are the chief producers. In New York the rock gypsum (usually 4 to 10 feet thick) lies in layers between shale and limestone strata of Silurian age, and it is quarried from the central to the western part of the state. In Michigan the rock-gypsum beds, commonly 5 to 20 feet thick, lie in Mississippian strata in the southern portion of the state. A great bed of exceptionally pure rock gypsum underlies about 25 square miles of Webster County, Iowa, in strata of late Paleozoic age. The Kansas gypsum deposits extend across the central part of the state in rocks of Permian age.

Rock gypsum is mainly used in making "plaster of paris," as a retarder in cement, and as a fertilizer (so-called "land plaster").

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Part II

AN INTRODUCTION TO HISTORICAL GEOLOGY

First Published, *October, 1916*
Reprinted, March, 1920

Second Edition, *December, 1922*
Reprinted, February, 1925, January, 1926
February, 1926, February, 1928

Third Edition, *December, 1928*
Reprinted, January, 1929, February, 1929
January, 1930

PRINTED IN THE U S A BY
THE PLIMPTON PRESS, NORWOOD, MASS.

PREFACE TO FIRST EDITION

It is the author's hope that this book may find a place as a class-book dealing with the historical geology portion of a one-year course in general geology, and that it may also serve as a text for special courses in historical geology. An elementary knowledge of what is generally comprised under dynamical and structural geology is presupposed. It is assumed that a proper amount of laboratory and field work will be pursued in connection with the text.

It will be seen that more introductory space is devoted to a discussion of the broad fundamental principles of historical geology than is customary in text-books. The experience of the author has been that careful attention to these general principles at the beginning of the subject is well repaid in satisfaction to both teacher and student when the great events of earth history are taken up in regular order.

A definite plan is strictly adhered to in the discussion of each period from the Cambrian to the Tertiary inclusive. Such definiteness of presentation, in spite of some objections which may be raised against it, should greatly aid the beginner, who must constantly compare periods and note the important changes in the evolution of both land-masses and organisms. The topical arrangements are such that any desired comparisons can be readily made. A plan of treatment, the same for both the Archeozoic and Proterozoic eras, permits a ready comparison of these two. By the very nature of the subject-matter, a somewhat more special method of discussion has been necessary for the Quaternary period.

Important features are the summaries of Paleozoic and Mesozoic history which will aid the student in fixing in mind the salient points in the history of those two great eras. It is believed that the two tabular summaries—one of Paleozoic life and the other of Mesozoic life — will be helpful. Group by group and period by period, from the Cambrian to the Cretaceous inclusive, the principal evolutionary changes in organisms are brought before the student at a glance by the use of these tables.

Students beginning the study of geology usually have either very little knowledge of biology or their study has not emphasized the classification of organisms. The evolution of organisms is a fundamental consideration in the study of earth history, and the instructor finds it well-nigh necessary to present to his classes outline classifications of plants and animals accompanied by brief descriptions of the more common types. Such matter is presented in the first chapter of this book.

In certain texts, especially those portions dealing with historical geology, there is a tendency to overwhelm the student by the introduction of a multiplicity of technical terms, especially the names of fossils. The present author's idea has been to reduce such terms to a reasonable minimum required for a proper understanding of the great principles of earth history. The genus and species names accompanying illustrations are given in the interest of scientific accuracy and with no thought that these are to be remembered by the student.

Various distinctly appropriate illustrations, more or less familiar because of their appearance in other text-books or manuals of geology, have not been abandoned merely for the sake of something new or different. Many of the illustrations, however, appear in a text-book here for the first time. Among the numerous original sources of illustrations, particular mention should be made of the publications of the United States Geological Survey, the New York State Museum, The American Museum of Natural History, and the Maryland Geological Survey.

The Macmillan Company, Henry Holt and Company, Ginn and Company, D. Appleton and Company, and John Wiley and Sons have generously allowed the use of various cuts. Careful attention has been given to the selection of only such views, fossils, diagrams, and maps as would systematically illustrate the text without overdoing this feature of the book.

The author is under particular obligation to Professor Bailey Willis of Stanford University for the use of his excellent series of paleogeographic maps of North America. These maps, together with his U. S. G. S. Professional Paper 71, have proved to be veritable storehouses from which to draw in the preparation of the manuscript of this book.

The well-known manuals and text-books of geology, especially

those by Dana, Chamberlin and Salisbury, Pirsson and Schuchert, LeConte, Scott, Norton, Blackwelder and Barrows, Geikie, Kayser, and De Lapparent, have been freely consulted, and due acknowledgment is here made for the help derived from these sources.

Among those who have read portions or all of the manuscript are the following: Dr. J. M. Clarke and Mr. C. A. Hartnagel of the New York State Museum; Professors W. B. Clark and C. K. Swartz and Mr. E. W. Berry of the Johns Hopkins University; and Dr. L. W. Stephenson of the United States Geological Survey. Special acknowledgment is made to these men for valuable suggestions and criticisms, but the author holds himself strictly responsible for all errors the book may contain.

WILLIAM J. MILLER

SMITH COLLEGE,
Northampton, Mass.,
August, 1916

PREFACE TO SECOND EDITION

In the second edition the subject-matter remains essentially unchanged, but various corrections and minor alterations of statement have been made. The writer is particularly grateful to several of the teachers who use the book for suggestions and criticisms which have been carefully considered so far as has been possible without altering the paging.

A feature of the book which should be especially emphasized is that distinctly more space is devoted to general principles of historical geology and physical history than to paleontology. In this respect the book differs notably from the customary textbook treatment of historical geology, and it is hoped that this feature will appeal not only to teachers who are not specialists in paleontology, but also to students who have little or no technical knowledge of biology.

W. J. MILLER

November, 1922.

PREFACE TO THIRD EDITION

The book has been thoroughly revised and brought up-to-date without changing the general plan of treatment. Great advances have been made in our knowledge of the geological history of North America since this book first appeared in 1916. In the light of this new knowledge, many changes have been made, involving corrections, omissions, and additions.

Facts and principles are emphasized with even less attention relatively to technical details than in the former editions. Thus the paleogeographic maps of North America not only have been made more accurate, but also they have been much simplified, so that the relations of land and sea, representing a given time, may be more easily recognized. Also many new interpretative statements have been added in the attempt to keep frequently before the reader the broader aspects and significance of the subject.

The book has been somewhat enlarged. Thus some of the line-cuts and half-tones have been replaced with better ones, and various new figures have been added; new topics are considered in Chapter II (General Principles); and the former brief treatments of the rocks and physical history of the Archeozoic, Proterozoic, Triassic, and Jurassic have been somewhat lengthened.

Taken altogether, the third edition is not only more accurate and up-to-date, but also it is a simpler and more readable account of historical geology, with emphasis on North America, than the former editions.

The wide use to which the book has been put in many colleges and universities has indeed been gratifying, and it is hoped that this new edition will be even more acceptable.

W. J MILLER

University of California at Los Angeles,
May, 1928.

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HISTORICAL GEOLOGY

WITH SPECIAL REFERENCE TO NORTH AMERICA

CHAPTER I

GENERAL PRINCIPLES

What Historical Geology Teaches

Historical geology deals with the evolution of earth structures and organisms. Its object is to arrange the events of earth history in the regular order of their occurrence. The records of these events are preserved in the rocks of the crust of the earth, the layers (strata) of which have been likened to the leaves of a great book. Many times the pages of this vast "nature-book" contain remarkable records and illustrations, while at other times they are comparatively barren. In order that the reader may, at the outset, form some general idea of the scope and character of the subject, the following summary of the more important conclusions derived from the study of earth history is here presented.

Inorganic Inferences. — 1. *The age of the earth must be measured by scores, if not hundreds, of millions of years.* One great mountain range after another has been built up and then worn away by the ordinary processes of erosion. Many scores of thousands of feet (in thickness) of strata have accumulated by the deposition of sediments slowly derived by the removal of many thousands of feet of materials from the lands. Such facts force us to the inference of a vast antiquity for the earth.

2. *The physical geography of the earth has been notably different in earlier geological time from that of the present.* For example, many millions of years ago (during the Ordovician period) an interior sea spread over much of what are now the Mississippi Valley and the Appalachian Mountain regions, as well as regions still farther westward.

3. *All, or nearly all, of the surface of the lithosphere has at some time, or times, been covered by sea water.* Stratified rocks of marine origin now constitute fully five-sixths of the exposed surface of the lithosphere, and it is certain that from most, at least, of the remaining surface such stratified rocks have been removed by erosion.

4. *The continents were roughly outlined in early geologic time.* This is proved by the facts that even the oldest known rocks contain much land-derived sediment of comparatively shallow water origin and that there are no deposits which show that great oceanic abysses ever extended across what are now continental areas. Much evidence points to an early development of oceanic basins and continental masses which have occupied essentially the same positions to the present time.

5. *During geologic time there has been a general tendency for the continental masses to become higher and grander.* There have been many oscillations of level, accompanied by transgressions or retrogressions of the sea, but the processes of elevation (relatively speaking) have been predominant, while, at the same time, the ocean basins have become generally deeper. The high elevation and great topographic diversity of the present-day lands seem to be unusual as compared to earlier periods of clearly recorded geological time.

Organic Inferences.[1] — 1. *Organisms inhabited the earth many millions of years ago.* All but possibly the very oldest known series of rocks contain organic remains.

2. *Throughout the known history of the earth organisms have continuously changed.* Each epoch of earth history or series of strata has its characteristic assemblage of animals and plants. The more ancient strata contain no species like those living today, the latter being found only in rocks of comparatively (geologically) recent date. Further, "the organisms which inhabited the earth during any geological epoch were descended from organisms of preceding epochs" (W. H Norton).

3. *The change in organisms has been progressive.* In early geological time the animals and plants were comparatively simple and low in the scale of organization and structure, and through the succeeding epochs higher and more complex types were gradually

[1] These statements of organic inferences follow, in the main, Norton's *Elements of Geology*

developed until the highly organized forms of the present time, culminating in man, were produced. It should be remembered, however, that not all change in organisms has been progressive, but rather only the general trend.

4. No *species once extinct has ever reappeared.* Numerous important species have lived through many epochs of geologic time, while others have had only brief existence. In no case, however, has a species once become extinct been known to reappear.

5 *While higher and higher types have been developed during geologic time, many of the earlier and simpler types have persisted.* Thus Foraminifers, which are exceedingly simple, single-celled animals, have lived in the sea from early geologic time to the present.

6 *The broader or larger biological groups of organisms have persisted longer than the smaller.* No subkingdom has ever become extinct, though species frequently have not outlived even a single geological epoch. As a rule, genera have survived longer than species, orders longer than genera, etc.

7. *The life history of the individual tends to recapitulate the evolution or history of the race.* A Frog, which is a typical Amphibian, shows certain fish-like characters during its embryonic development, as, for example, the presence of gills and tail. Again, the modern Crab, which is a Crustacean, shows a gradual shortening of the tail portion during its embryonic development. The earliest known Crustaceans were practically all long tailed.

Fossils and Their Significance

Traces or remains of plants and animals preserved in the rocks are known as fossils. The term originally referred to anything dug out of the earth, whether organic or inorganic, but for many years it has been strictly applied to organisms. Paleontology, which literally means "science of ancient life," deals primarily with fossils.

Darwin thought that the stratified rocks contain only a very incomplete record of the geologic history of life. Though many thousands of species of fossils have been described from rocks of all ages except the very oldest, and more are constantly being brought to light, it must be evident that, even where conditions

of fossilization were most favorable, only a small part of the life of any period is represented by its fossils. Comparatively few remains of organisms now inhabiting the earth are being deposited under conditions favorable for their preservation as fossils. So it has been throughout the long periods of earth history, though the fossils in the rocks known and unknown are a fair average of the groups of organisms to which they belong. In spite of such imperfections in the life record, it is, nevertheless, remarkable that so vast a number of fossils are embedded in the rocks, and from these we are enabled to draw many fundamental conclusions regarding the history of life on our planet.

Preservation of Fossils. — 1. *Preservation of the entire organism by freezing.* Fossilization by this method is rare, though remarkable examples are afforded by extinct species of the Mammoths and Rhinoceroses, the bodies of which, with flesh, hide, and hair intact, have been found in frozen soils in Siberia.

2. *Preservation of the entire organism by natural embalmment.* Fine examples are the perfectly preserved Insects in the famous amber of the Baltic Sea region. This amber is a hardened resin, the Insects having been caught in it while it was still soft and exuding from the trees.

3. *Preservation of only the hard parts of the organisms.* This is a very common kind of fossilization in which the soft parts have disappeared by decomposition, while the hard parts, such as bones, shells, etc., remain. Fossils of this kind are abundant in rocks of later geological time, though original shell material is frequently found, even in very ancient rocks.

4. *Preservation of carbon only* (*carbonization*). This is particularly true of plants where, as a result of slow chemical change or decomposition, the hydrogen and oxygen mostly disappear, leaving much of the carbon, but with the original structure often beautifully preserved. Many excellent examples are furnished by the fossil plants of the great coal (Pennsylvanian) age.

5. *Preservation of original form only* (*casts and molds*). Fossils of this class, which are very abundant, show none of the original material, but only the shape or form has been preserved. When a fossil becomes embedded in sediment, which hardens around the entire organism or any part of it, and the organism then decomposes or dissolves away, a cavity only is left and this is called a

mould. A cast may be formed by filling a mould with some substance such as sediment or mineral matter carried by underground water, or by filling a hollow organism like a shell with some solid substance. The cast reproduces the internal form of the shell or organism. Frequently original shell, mould, and cast may be seen in a single specimen, while more commonly the original shell has been dissolved away. Only in rare instances have casts of wholly soft animals, or the soft parts of other animals, such as the Jelly-fishes and Cuttle-fishes, been found in ancient rocks.

6. *Preservation of original form and structure (petrifaction).* Here again we have a common kind of fossilization. When a plant or hard part of an animal has been replaced, particle by particle, by mineral matter, we have what is called petrifaction. Often organic matter, such as wood, or inorganic matter, such as a carbonate-of-lime shell, have been so perfectly replaced that the original minute structures are preserved as in life. Conditions favorable for the petrifaction of flesh seem never to have obtained.

7. *Preservation of tracks of animals.* Footprints of animals, made in moderately soft mud or sandy mud which soon hardens and becomes covered with more sediment, are especially favorable for preservation. Thousands of examples of tracks of great extinct Reptiles have been found in the red sandstone of the Connecticut River Valley alone. Tracks or trails of Clams or similar animals, and burrows of Worms, are also not uncommon in the ancient rocks of the earth.

Rocks in which Fossils occur.—1. *Land deposits.* Old soils sometimes contain bones or other organic remains. Peat-bogs are especially favorable for the preservation of fossils, as, for example, the wealth of plants directly associated with the resulting coal seams; remains of animals, such as Frogs, Snakes, etc., which inhabited the swamp or bog; and the bones of other animals which wandered in and became entombed. Cave deposits often cover animal remains, many bones of extinct animals, even including prehistoric Man and the things he used, having been found in such deposits. Wind-blown deposits, like dune-sand, loess, and desert deposits, may contain plant or animal remains. Interglacial deposits sometimes contain fossils, as, for example, the layers of vegetable matter with occasional bones of animals found in the interglacial deposits of the upper Mississippi Valley. Lavas

rarely contain fossils, but volcanic ash deposited in water may be rich in organic remains, this being especially true of certain portions of the western interior of the United States.

2. *River and lake deposits.* River deposits often carry river forms themselves, or land forms which fell into the stream and became entombed in its deposits. Lakes offer very favorable conditions for fossilization. "Surrounding trees drop their leaves, flowers, and fruit upon the mud-flats, Insects fall into the quiet waters, while quadrupeds are mired in mud or quick-sand and soon buried out of sight. Flooded streams bring in quantities of vegetable debris, together with the carcasses of land animals drowned by the sudden rise of the flood" (W. B. Scott).

3. *Marine deposits.* By far the largest number and variety of organic remains are found in rocks of marine origin, because on the sea bottom the conditions for their preservation have been most favorable. The distribution of fossils in strata of marine origin is, however, exceedingly irregular, ranging from those strata which are almost entirely made up of fossils to others which are nearly barren. Longshore deposits are usually not rich in fossils, because of the grinding action of the waves, while deposits formed in the quiet waters off shore often contain vast numbers of fossils. Many conditions have produced great diversity in the distribution of marine organisms throughout known geologic time: temperature, depth of water, supply of food, degree of salinity, nature of the sea bottom, clearness of the water, etc. The oldest fossiliferous strata seem to contain practically no land forms, probably because land forms were but slightly, if at all, developed so early. In marine strata of more recent date terrestrial organisms are often found, especially in delta deposits, where such remains have been swept into the sea at the mouths of rivers.

Significance of Fossils. — It would be difficult to overestimate the value of fossils in the study of earth history. They furnish most important evidence regarding earth chronology, ancient geographic and climatic conditions, as well as a basis for a proper understanding of the evolution relations and distribution of modern organisms.

"The materials with which the paleontologist must deal are the dead, unchangeable fossils, dug up from the rocks of the earth's crust, but the problems which arise from the study of these materials are far from dead, being filled with living interest

and giving vitality to the whole field of historical geology. These now defunct fossils were once living, growing organisms, which were associated together in innumerable faunas, which lived in all portions of our earth, which followed one another in almost endless succession from the earliest recorded period of geological history to the present time, and which were adapted to all sorts of environmental conditions on the land and in the sea."[1]

Leonardo da Vinci (1452–1519), the famous artist, architect, and engineer, while engaged in canal construction in northern Italy, saw many fossils embedded in the rocks. He concluded that these organisms had actually lived in marine water which once spread over the region. William Smith (1769–1839) of England was, however, the first to recognize the fundamental significance of fossils for determining the relative ages of stratified rocks. His announcements, based upon much careful detailed work, were made in the latter part of the eighteenth century and the early part of the nineteenth century. He has been called by the English the "Father of Historical Geology."

1. *Earth chronology.* In any given region the best way to learn the relative ages of the stratified rocks is to determine their "order of superposition," the general assumption being that the older strata underlie the younger because the underlying sediments must have been first deposited. While this is a fundamental method, it is very limited in its application when used alone in regard to the construction of the whole earth's history. The succession of strata seen in any one locality or region represents only a small part of the earth's entire series and this, taken in connection with the fact that the lithologic character of strata of the same age frequently changes, makes it clear that "order of superposition" alone will not suffice to determine the relative ages of sedimentary rocks on a single continent or even large portion of a continent, not to mention the utter inadequacy of the method when applied to comparing the relative ages of strata of different continents.

"Order of superposition," however, when used in connection with the fossil content of the strata, furnishes us with the method of determining earth chronology. "Life, since its introduction on the globe, has gone on advancing, diversifying, and continually rising to higher and higher planes . . . Accepting, then, the undoubted fact of the universal change in the character of the organic

[1] S. Weller: *Bul. Geol. Soc. America,* Vol. 38, 1927, p. 276.

beings which have successively lived upon the earth, it follows that rocks which have been formed in widely separated periods of time will contain markedly different fossils, while those which are laid down more or less contemporaneously will have similar fossils. This principle enables us to compare and correlate rocks from all the continents and, in a general way, to arrange the events of the earth's history in chronological order . . . A geological chronology is constructed by carefully determining, first of all, the order of superposition of the stratified rocks, and next by learning the fossils characteristic of each group of strata . . . The order of succession among the fossils is determined from the order of superposition of the strata in which they occur. When that succession has been thus established, it may be employed as a general standard."[1]

The student should bear in mind that strata cannot be determined as precisely contemporaneous, because geologic time has been very long and the evolution of organisms very slow, and almost exactly similar fossils may be expected in strata showing an age difference of at least some thousands of years. Also, at any given ancient time of earth history, as now, organisms were not the same in all parts of the world, so that rocks formed at exactly the same time in different parts of the world always show certain differences in fossil content. As compared with the vast length of geologic time, however, practical contemporaneity of the strata can usually be determined.

For the determination of geologic chronology, certain organisms are more valuable than others, the best being those which have had wide geographic distribution and short geologic range. For example marine organisms, which live near the ocean surface (so-called pelagic forms) and are easily distributed over wide areas, while, at the same time, the species are extant for only a comparatively short time, are the best chronologic indicators. The Graptolites of the early Paleozoic era furnish excellent illustrations.

2. *Past physical geography conditions.* Typical stratified rock occupying any region proves the former presence of water over that region. By the study of the fossils we can further usually tell whether the water was ocean or lake, fresh or salt, open sea or arm

[1] W. B. Scott. *An Introduction to Geology*, 2nd edition, pp. 521–522 and 525.

of the sea, deep or shallow, close to or far from land, etc. Lithologic character alone may give some idea as to the depth of water and proximity to land where a given stratum was deposited, but the presence of considerable numbers of terrestrial organisms gives important additional data. Thick limestones filled with fossil Corals point to long-continued conditions of clear sea water. Tree stumps, on the other hand, with roots still in their original position, plainly prove a former land surface. By means of fossils, many land areas have been proved to have existed as effective barriers to migrations of marine organisms. Certain lands now separated by water may be shown to have been formerly connected, as was true of Alaska and Siberia, by a land connection across Bering Strait. Also the fossils found in the rocks of the Isthmus of Panama show that North and South America were there connected at a comparatively recent time in earth history.

3. *Past climatic conditions.* Some strata afford an idea of the climatic conditions under which they were laid down. Thus salt and gypsum beds, more or less associated with certain red sandstones or shales, indicate an arid climate at the time of their formation. But the study of fossils is much more fruitful in this connection. Certain strata in southern England contain fossil Palms, Gourds, Crocodiles, etc., thus proving a subtropical climate for the time of their origin. Other strata, representing a later date in southern England, carry remains of Arctic animals and hence indicate a cold climate for that time. The finding of Walrus remains in New Jersey and Musk-ox remains in Arkansas indicate a former colder climate for those regions. Again, many fossil Palms, Ferns, and other temperate to subtropical plants, as well as animals, clearly point to former warmer climate in those same regions.

Much strong evidence for climatic conditions over various portions of the earth during different geologic periods has been furnished by the study of true marine organisms. Certain kinds of Corals live only in shallow tropical seas, and so, if in any region we find a bed of limestone rich in Corals of this kind, it is to be inferred that this limestone was formed in warm, shallow sea water. Such coral limestones are known even in the interior of North America.

In deducing climatic inferences, as above explained, certain care must be exercised, because we are not justified in assuming that

because a given species now lives under warm climatic conditions, every species of the same genus has lived under similar conditions. When, however, we are dealing with species still living, or in older rocks, with whole groups of organisms pointing to certain climatic conditions, we are reasonably safe in our inferences.

4. *Relations and distribution of modern organisms.* It is evident that, if we are to properly understand the present-day relations and distribution of organisms, we must learn about their ancestry and history, because all modern plants and animals have descended directly from those which lived in earlier geologic epochs. In many cases existing plants or animals, notably different in structure, can be traced back to a common ancestry. Again, certain peculiarities in the distribution of some of the present-day animals are readily explained in the light of their geologic ancestry and habitats. A good example is Australia, where practically all of the present-day Mammals (barring those introduced by Man) are of very simple types, that is, non-Placentals such as the Kangaroo, Spiny Ant-eater, etc., found only in and close to Australia, and which are clearly much more like the Mammals of distinctly earlier geologic time than like typical Mammals of the present day. The explanation is that Australia was separated from Eurasia before the higher (Placental) Mammals had been evolved, and that the very different, or probably much less severe, struggle for existence in isolated Australia has not been favorable for the evolution of Placentals as was the case elsewhere.

Outline Classifications of Animals and Plants

Since a knowledge of the classifications of animals and plants and the principal characteristics of the more important groups of organisms is a fundamental consideration in the study of the life of each period, and in understanding the bearings of these life records upon the great doctrine of organic evolution, outline classifications of plants and animals, with simple explanations, are here given. The classifications are necessarily very brief, and no great degree of biologic refinement is intended. Rather the purpose is to have a convenient arrangement, essentially in biologic order, of the principal groups of organisms, commonly occurring as fossils, to form a simple basis for the discussion of the life of each period of geologic history as presented in this text-book.

Organisms are divided into many groups, such as kingdoms (e.g. plant and animal), subkingdoms, branches, classes, orders, genera, and species. A species is "the smallest group of plants or animals having certain characters in common that make them different from all other plants or animals" (G. W. Hunter). Species are grouped together into larger subdivisions called genera (singular "genus"), etc. The scientific name of an organism generally consists of two words — the first signifying the genus and the second the species, as, for instance, "Archeopteryx macrura," which literally means "primitive winged creature with a long tail," and is the name of the earth's first known Bird.

Plants. —

- I. CRYPTOGAMS
  - 1. Thallophytes
    - 1. Algæ (e.g. Sea-weeds and Diatoms).
    - 2. Fungi (e.g. Mushrooms).
  - 2. Bryophytes (e.g. Mosses)
  - 3. Pteridophytes
    - 1. Lycopods (e.g. Club-mosses)
    - 2. Equisetæ (e.g. Horse-tails).
    - 3. Filicales (e.g. Ferns).
- Pteridosperms (e.g. Seed-ferns).
- II. PHANEROGAMS
  - 1. Gymnosperms
    - 1. Cycads
    - 2. Cordaites
    - 3. Conifers (e.g. Pines, Spruces, etc.).
  - 2. Angiosperms
    - 1. Monocotyledons (e.g. Grasses, Lilies, etc.).
    - 2. Dicotyledons (e.g. Oaks, Roses, etc.).

I. The CRYPTOGAMS comprise all of the flowerless and seedless plants, the reproductive organs being single cells called spores.

1. *Thallophytes* show "no definite axis of upward growth, and no distinction of root, stem, and leaf. They all consist entirely of cellular tissue, being entirely destitute of wood" (J. D. Dana). In general there are two groups of Thallophytes — Algæ and Fungi — the former containing chlorophyl and able to live upon inorganic substances, while the latter are without chlorophyl and live upon organic matter.

2. *Bryophytes* are like Thallophytes in being woodless, but they develop a sort of axis of upward growth and possess leafy stems.

3. *Pteridophytes* (Fig. 118) comprise the highest types of the seedless plants, and these have a clear distinction of root, leaf, and stem, the stem possessing woody fibres. These plants have been much more favorable for fossilization than most of the foregoing, and they assume considerable importance in the fossil

forests, especially of the great Coal (Pennsylvanian) age. (1) *Lycopods* usually have branching stems upon which are crowded numerous small, single-nerved, needle-like leaves. Modern representatives are the small "Ground-pines" or "Club-mosses" so familiar as Christmas decorations. (2) *Equisetæ* have erect growth, hollow or pithy segmented stems, and leaves arranged in whorls around the stems. (See Fig. 118.) Modern representatives are the "Horse-tails," which are rush-like plants often seen along our streams. Both Lycopods and Equisetæ grew to be large trees during the great Coal (Pennsylvanian) age. (3) *Filicales* or *Ferns* of temperate climates usually have fronds springing from a buried stem, while tropical forms may have fronds arranged around the summit of tree-like trunks.

Pteridosperms are fern-like plants (Fig. 119) which have been recently recognized as a group seemingly intermediate between the highest Cryptogams (i.e. Filicales) and the lowest Phanerogams (i.e. Cycads). They possess seeds but not true flowers, and show certain other characters intermediate between Ferns and Cycads. These plants are all extinct, but from the fossil and evolution standpoints they are important.

II. PHANEROGAMS comprise the seed-bearing, flowering plants whose reproductive organs are stamens and pistils and whose seeds contain embryo plants.

1. *Gymnosperms* or the so-called "naked seed" plants include all those which do not have their seeds inclosed in a case or ovary. They possess very simple flowers, and their mode of growth is exogenous.[1] (1) *Cycads* are palm-like in appearance (Fig. 160), certain of them being erroneously called "Sago Palms." True Palms, however, are Angiosperms with endogenous growth. In some ways Cycads also resemble the Ferns. Though now uncommon, the Cycads are of considerable geological importance. (2) *Cordaites* (Fig. 120) are now entirely extinct, but during the latter part of the Paleozoic era they grew extensively as tall, slender trees "with trunks rising to great height before branching, and bearing at the top a dense crown, composed of branches of various orders, on which simple leaves of large size were produced in abun-

[1] Exogenous plants grow from without; have distinct bark, wood, and pith, and show concentric rings of growth, a new ring usually being added each year Endogenous plants grow from within and have neither pith nor concentric rings of growth.

dance" (D. H. Scott). (3) *Conifers* include the familiar Pines, Spruces, etc., all of which have dense, cone-like clusters of very simple flowers.

2. *Angiosperms* all have their seeds enclosed in a case or ovary, and have more highly developed, typical flowers as well as greater complexity than the Gymnosperms. (1) *Monocotyledons*, such as the familiar Palms, Grasses, Lilies, etc., produce only a single leaf from the germinating seed, are endogenous, and usually have parallel-veined, simple leaves. (2) *Dicotyledons*, such as Oaks, Roses, and many other familiar plants, produce two leaves from the embryo, are exogenous, and usually have net-veined leaves.

Animals.[1] —

Sub-kingdoms		*Classes*	
I. Protozoans		1. Rhizopods	1. Foraminifers (calcareous shelled)
			2. Radiolarians (siliceous shelled).
		2.	Not fossil
		3.	
		4.	
II. Porifers (e.g. Sponges).			
III. Cœlenterates		1. Hydrozoans (e.g. Jelly-fishes, Graptolites).	
		2. Anthozoans (e.g. Corals)	
IV. Echinoderms	1. Pelmatozoans	1. Cystoids (Bladder-like forms)	
		2. Blastoids (Bud-like forms)	
		3. Crinoids (Lily-like forms)	
	2. Asterozoans.	1. Ophiuroids (e.g. Brittle-stars)	
		2. Asteroids (e.g. common Star-fishes).	
	3. Echinozoans	1. Echinoids (e.g. Sea-urchins)	
		2. Holothuroids (e.g. Sea-cucumbers).	
V. Vermes (e.g. Worms)	Not important as fossils		
VI. Molluscoids.		1. Bryozoans (e.g. Sea-mosses)	
		2. Brachiopods (e.g. Lamp-shells).	
VII. Mollusks		1. Pelecypods (e.g. Oysters, Clams)	
		2.	Not common as fossils
		3.	
		4. Gastropods (e.g. Snails)	
		5. Cephalopods	1. Tetrabranchs (e.g. Ammonites, Nautilus)
			2. Dibranchs (e.g. Squids, Cuttle-fishes).
VIII. Arthropods.		1. Crustaceans	1. Merostomes (e.g. Horse-shoe Crabs).
			2. Trilobites
			3. Eucrustaceans (e.g. Crabs, Lobsters)
		2. Arachnids (e.g. Spiders, Scorpions, Eurypterids)	
		3. Myriapods (e.g. Centipedes)	
		4. Insects (e.g. Grasshoppers, Flies)	
IX. Vertebrates.		1. Ostracoderms (e.g. Armor-fishes)	
		2. Fishes	
		3. Amphibians (e.g. Frogs, Salamanders).	
		4. Reptiles (Lizards, Snakes)	
		5. Birds	
		6. Mammals (e.g. Dog, Man).	

[1] This classification is after Zittel with certain modifications and omissions.

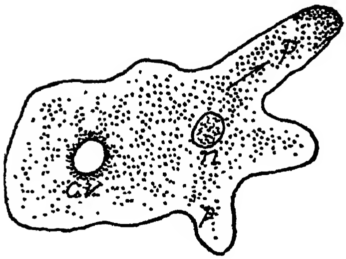

Fig 1

A Protozoan (Amœba) without a shell. Greatly enlarged (From Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company)

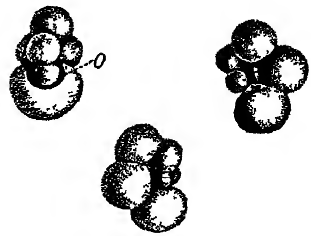

Fig 2

Shelled Protozoans (Foraminifers) (From Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company)

I. Protozoans are the simplest of all animals. They consist of single cells of protoplasm and are without distinct organs. *Rhizopods* are the only Protozoans which are encased in shells, the

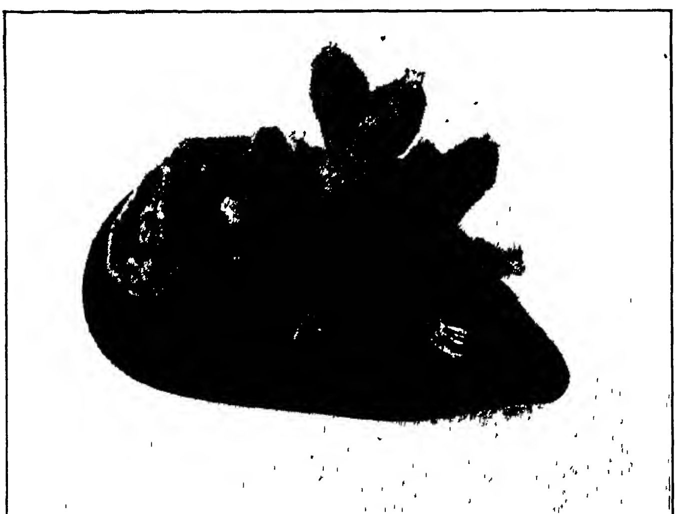

Fig. 3

Sponges on a shell. (Courtesy of the American Museum of Natural History)

Foraminifers having carbonate of lime shells and the *Radiolarians* shells of silica. Though very small, these shells have frequently built up limestone (chalk), or chert beds.

II. Porifers or Sponges, which are the simplest of the many-celled animals, are sac-like forms supplied with numerous pores or canals through which water containing food circulates to feed the cells. Distinct organs are lacking. Most Sponges have either siliceous or calcareous skeletons.

III. Cœlenterates are also very simple many-celled animals, but they possess distinct mouth, body (or stomach) cavity, and usually have radiating tentacles surrounding the mouth. The canal system of the Sponges is absent. *Hydrozoans* are little creatures consisting of tube-like sacs with mouth at one end surrounded by tentacles. *Anthozoans* are very much the same, but have a more or less distinct esophagus, and have the body cavity divided by radiating vertical partitions. Some Hydrozoans and Anthozoans colonize and some do not. Among the former, the *Graptolites* (now extinct) are numerous and important in early Paleozoic rocks, while the latter or *Corals* have always been prominent since pretty early Paleozoic time.

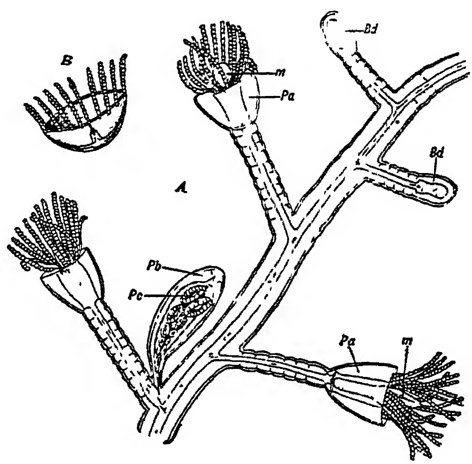

Fig. 4

Modern Hydrozoans Part of a colony much enlarged. (From Schuchert's "Historical Geology," permission of John Wiley and Sons)

IV. Echinoderms possess a distinct body cavity which contains the digestive or alimentary canal, distinct nervous system, and a water circulatory system. Most Echinoderms are radially segmented and protected by shells. 1. *Pelmatozoans* are characterized by having segmented stems by which they are attached to the sea-floor or some object during at least part of their existence.

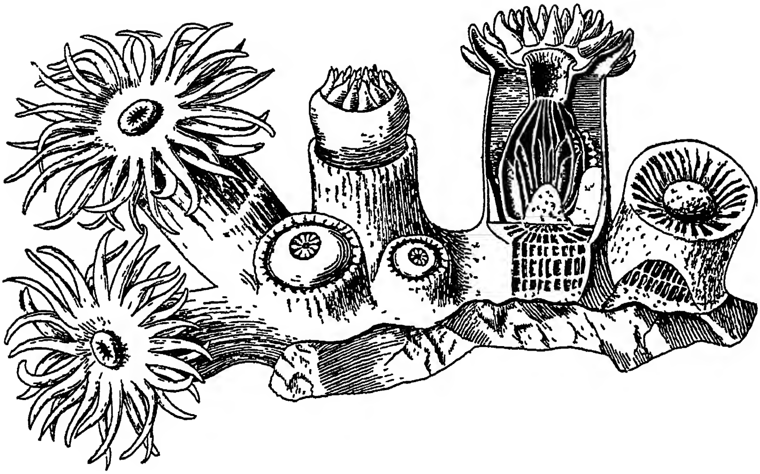

Fig. 5

A group of modern Corals showing the internal structure of one individual. (After Pfurtscheller, from Schuchert's "Historical Geology," permission of John Wiley and Sons)

Among Pelmatozoans, the *Cystoids* are small, bladder-like forms with irregular radial arrangement of plates of the shell and arms

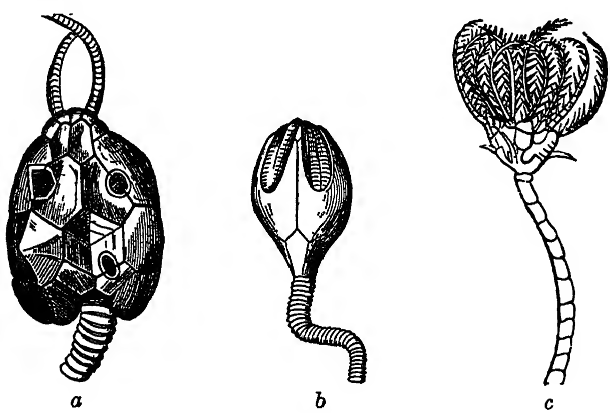

Fig 6

Stemmed Echinoderms (Pelmatozoans). *a*, Cystoid, *b*, Blastoid, *c*, Crinoid.

wholly absent or only slightly developed; the *Blastoids* are bud-like forms with plates of the shell in very regular radial order, and without arms; and the *Crinoids* are lily-like forms with regular radial arrangement of plates of the shell, and with long, feathery arms surrounding the mouth. 2. *Asterozoans* are the free-moving, star-shaped Echinoderms usually with five arms or rays radiating

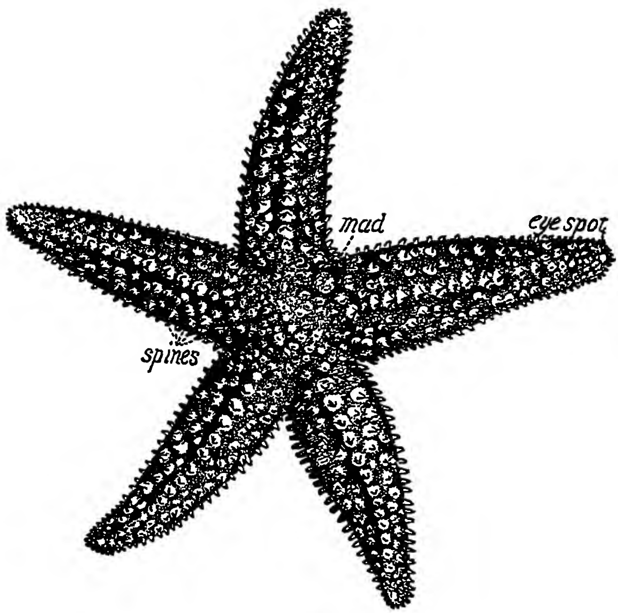

Fig. 7

A modern Asterozoan ("Starfish") (From Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company.)

from a central disk. Of these the *Ophiuroids* (Brittle-stars) have slender, flexible rays very distinct from the central disk, while the *Asteroids* have thicker rays not so sharply separated from the central disk, and the alimentary canal extends into the rays. 3. *Echinozoans* are not free-moving, are without free arms, and are stemless. Of these the *Echinoids* (Sea-urchins) have hard shells made up of calcareous plates usually immovably joined and covered with numerous movable spines; and the *Holothuroids*

(Sea-cucumbers) are soft bodied, with leathery covering, tentacles around the mouth, and skeletons of scattering limy spicules.

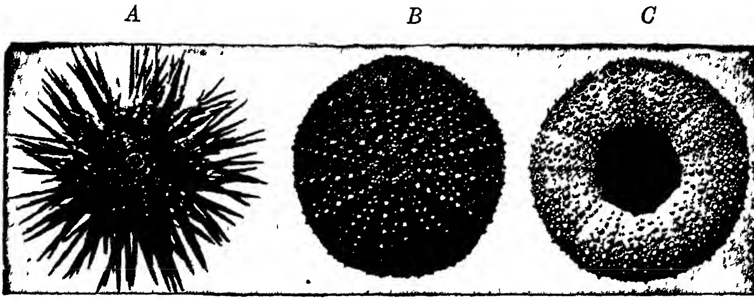

Fig 8

Modern Echinoids ("Sea-urchins"), one with spines in position. (After Coe, from Schuchert's "Historical Geology," permission of John Wiley and Sons)

V. Vermes or Worms include a large group of forms more complex in organization than the preceding groups Some are segmented and others are not. Since hard parts are very rarely developed, the Worms are of no great importance as fossils, their

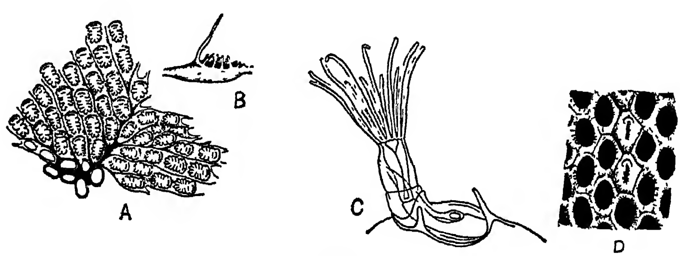

Fig 9

Bryozoans *A*, portion of modern colony seen from above (x15), *C*, an individual expanded; *D*, fossil form. *A–C* after Verrill and Smith; *D*, from Ulrich (From Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company.)

presence usually being indicated by trails, burrows, or tubes made in mud or sand.

VI. Molluscoids, as the name suggests, bear a resemblance to the Mollusks. They differ from the Anthozoans, Echinoderms,

Worms, and Arthropods in the entire absence of body segmentation. Absence of distinct head and foot, the lower development of the nervous system, and usual lack of locomotive power distinguish them from Mollusks. A highly characteristic feature of the Molluscoids is a sort of collar or ridge, bearing fringe-like tentacles around the mouth. The soft parts of the animal are protected by a limy or chitinous covering. 1. *Bryozoans* form tiny moss-like tufts which nearly always colonize and suggest the Anthozoans in outward appearance, though they are much more highly organized. With few exceptions the Bryozoans secrete calcareous Coral-like skeletons. 2. *Brachiopods* have two distinct shells (valves) enclosing the soft body of the animal which contains two long, limy, variously shaped, sometimes coiled, supports. In fossil form the Brachiopods are most readily distinguished from certain Mollusks (Pelecypods), which are also bivalves, by the bilateral symmetry of

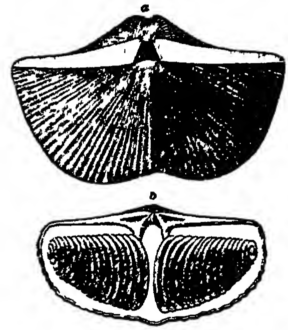

Fig. 10

Brachiopod shells (fossil forms). The lower one shows internal spiral supports

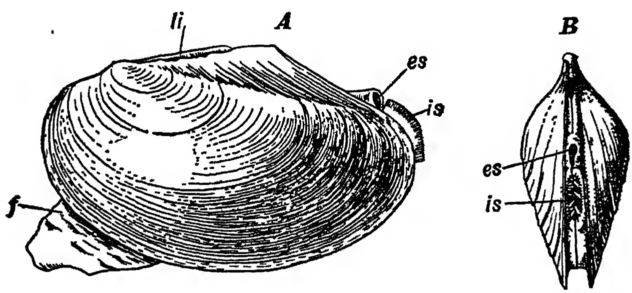

Fig. 11

A modern Pelecypod *A*, side view; *B*, end view. (After Howes, from Schuchert's "Historical Geology," permission of John Wiley and Sons)

the shells. That is, a plane of symmetry may be passed through the valves at right angles to the hinge line. Bryozoans and Brachiopods are both very abundant as fossils, especially in the older rocks.

VII. Mollusks, like Molluscoids, lack segmentation, but they are more highly organized with more or less distinctly developed body and locomotive organs. Nearly all have shells, generally external, and gills for respiration 1. *Pelecypods* (e.g. Oysters and Clams) are always supplied with a pair of external shells nearly alike and hence they are bivalves, but they differ from Brachiopods (also bivalves) in the absence of bilateral symmetry. The head is less distinct than in the other Mollusks. 2. *Gastropods* (e.g Snails) have distinct head with eyes and one or two pairs of tentacles, and they are almost invariably covered by a one-chambered shell. 3. *Cephalopods* have well-defined foot; head armed with tentacles; and large complex eyes. They propel themselves rapidly by forcible ejection of water. *Tetrabranchs* (e.g. modern Pearly Nautilus) are the so-called chambered Cephalopods because the external shell, straight or coiled, is divided into compartments. They are four-gilled and with numerous tentacles. *Dibranchs* (e.g. so-called Cuttle-fishes) are two-gilled; with either eight or ten tentacles; bag for secreting an inky fluid; and almost invariably without external shell. Usually there is a sort of cigar-shaped internal shell. Mollusks of all classes have been abundantly preserved in rocks of all but the earliest geologic ages.

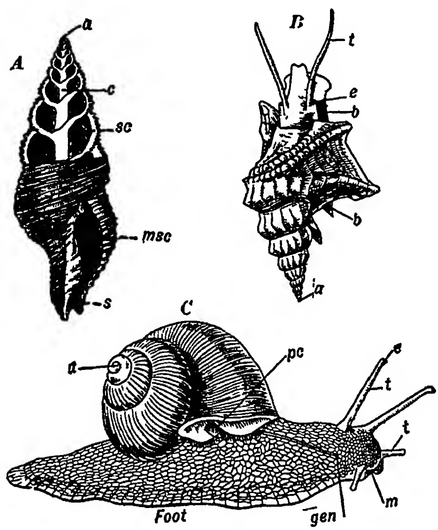

Fig 12

Gastropods A and B, marine forms; C, land Snail (From Schuchert's "Historical Geology," permission of John Wiley and Sons)

VIII. Arthropods are highly characterized by longitudinal body segmentation; jointed appendages (usually a pair from each segment); and usually by a pair of nerve centres in each segment. 1. *Crustaceans* (e.g. Lobsters and Crabs) are water animals breath-

ing by means of gills or through the body; usually with two pairs of well-developed antennæ (feelers); and covered with a chitinous or calcareous crust or shell. 2. *Arachnids* (e.g. Spiders and Scorpions) are land Arthropods breathing by air-sacs; have four pairs of legs; and no antennæ. 3. *Myriapods* (e.g. Centipedes) are land Arthropods with numerous legs; one pair of antennæ; and no wings. 4. *Insects* (e.g. Grasshoppers and Butterflies) are also land Arthropods with one pair of antennæ, but with three pairs of legs, and nearly always with wings.

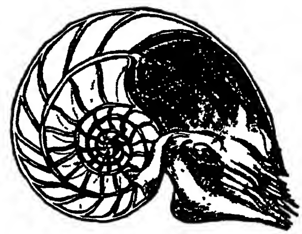

Fig. 13

A modern chamber-shelled Cephalopod (Nautilus) showing the internal shell structure.

IX. Vertebrates are eminently characterized by the possession of a vertebral column, which, in all but the very low forms, is a thoroughly ossified backbone. Vertebrates include the highest known of all animals. 1. *Ostracoderms* (e.g. Armour-fishes, now wholly extinct) are among the very simplest of Vertebrates (see Fig. 95). They are of particular interest from the standpoint of the evolution of the Fishes and higher Vertebrates. Characteristic features will be

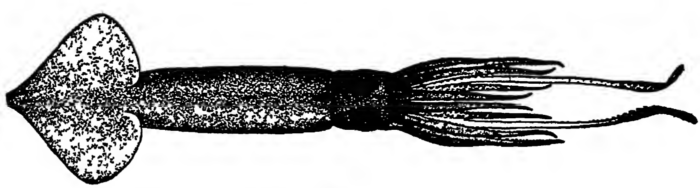

Fig. 14

A modern Squid. (After J. H. Blake, from Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company)

given beyond in connection with the life of the Devonian period. 2. *Fishes* always live in water; have distinct cartilaginous or bony vertebral column; distinct jaws; pairs of fins; and gills. Subclasses of Fishes will be described later. 3. *Amphibians* (e.g. Frogs and Salamanders) live either in water or on land. In the early stage of development of the individual (e.g. Tadpole stage), they are aquatic, and breathe by gills, while in the adult stage they breathe by lungs and are largely terrestrial in habit. They never

have fins 4. *Reptiles* (e.g. Snakes and Crocodiles), though in many ways like Amphibians, never have gills, and always have scales or bony plates developed from the skin. They are the most highly organized cold-blooded animals. 5. *Birds* are plainly distinguished from all other animals by their covering of feathers. They are too familiar to need special description. They are warm-blooded creatures with well-developed heart and circulation of blood. 6 *Mammals* (e.g. Dog and Man) include the highest of all organisms, a characteristic being that they all suckle the young. They are mostly quadrupeds, covered with hair, and dwellers on land. The Whale is an exceptional mammal.

Vertebrate fossils are common and of special interest because they show the development of the higher animals. The simplest (Ostracoderms) have been found in rocks of Ordovician age (see below), and higher and higher forms were gradually introduced and developed until the most complex Mammals appeared in comparatively recent time.

CHAPTER II

GENERAL PRINCIPLES — CONCLUDED

Correlation of Rock Formations

By Stratigraphy is meant that branch of geologic science which "arranges the rocks of the earth's crust in the order of their appearance, and interprets the sequence of events of which they form the records" (A. Geikie). All stratified rocks may be subdivided into formations or groups of strata, each of which is marked either by a characteristic facies or assemblage of fossils, or, to greater or less extents, by similarity of lithologic features, or by both. A rock formation is generally considered to be a mappable unit, that is its area can be delimited upon a geologic map. Subdivisions of formations are usually called members. By correlation of formations is meant the determination of the age equivalence, or practical equivalence, of rock groups or formations in various parts of the earth. Exact contemporaneity for widely separated districts cannot be expected as above explained in chapter 1. In general the criteria of correlation may be divided into two classes, namely, geological (physical) and paleontological (biological).[1]

I. Geological (physical) criteria. In many cases formations carry no fossils or very few, and it is then necessary to seek means of correlation without their aid. None of the geological (physical) methods can, however, be applied over wide areas such as opposite sides of a continent, or different continents. For such wide correlations, criteria derived from a study of fossils only can be used.

1. *Continuity of deposit.* If, as shown in the accompanying diagram (Fig. 15), continuity can be traced from A to B, it is quite certain that the rock masses at A and B are of the same, or very nearly the same, age. There is probably no more important means of correlation used by the geologist except over wide areas.

[1] The criteria of correlation as here presented are based largely upon university lectures by Dr. W. B. Clark

2 *Similarity of materials.* Rock formations not actually continuous, though not too widely separated, are often correlated by noting similarity or identity of lithologic character, especially if there are any locally peculiar features. Earlier geologists were inclined to overwork this method of correlation by applying it over areas of too great extent, in some cases even suggesting identity of age of deposits on opposite sides of the ocean by this means The danger of such application is apparent when we realize that, for example, a sandstone of very early (Cambrian) age may be exactly like sandstone of much later (Tertiary) age.

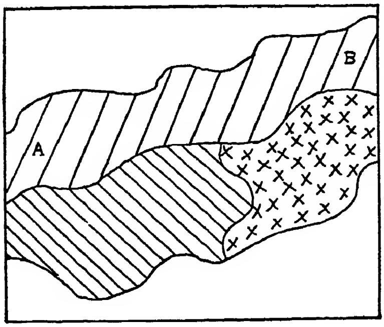

Fig 15
Diagram to illustrate correlation of rock formations by continuity of deposit. (W. J M)

3. *Similarity of sequence.* A succession of strata in two places like A and B (Fig. 16), and not continuous on the surface, may be correlated on the basis of similarity of sequence, particularly when each formation at one place (A) shows little or no difference in lithologic character or thickness as compared with each formation at the other place (B).

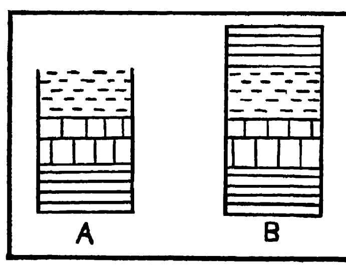

Fig. 16
Diagram to illustrate correlation of rock formations by similarity of sequence. (W J. M.)

4. *Similarity of degree of change, or structural relations.* By finding similarly changed or metamorphosed rocks in the same vicinity, they may thus be correlated. For instance, in the accompanying diagram (Fig. 17) it is evident that the rocks of group A are older than those of group B, and these in turn older than C. Outcrops over limited areas at least can thus be placed in one of these three groups. By way of illustration, the (pre-Paleozoic) rocks of the Highlands of the Hudson in southeastern New

York are highly metamorphosed and folded, with indurated, folded (Ordovician) strata resting upon their north side, and indurated, non-folded, and slightly tilted (Triassic) strata coming against them on the south side. Each of these groups of rocks represents a distinctly different geologic age. This method cannot be used over wide areas such as different parts of a continent, because for instance, certain strata (Cretaceous) in the eastern part of the United States may be unconsolidated and horizontal, while rocks of the same age are highly folded in the western United States.

5. *Study of adjacent lands.* Examination of the materials of

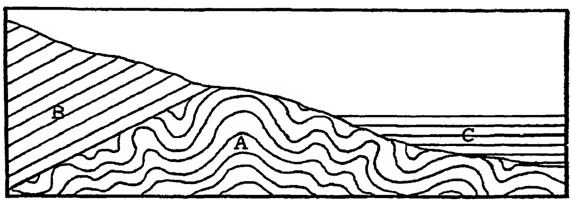

Fig. 17
Diagram to illustrate correlation of rock formations by degree of change or structure. (W. J. M.)

the Coastal Plain of our Atlantic sea-board clearly shows them to have been largely derived from the rocks of the Piedmont Plateau and Appalachians, and hence these Coastal Plain materials are the younger. Also the peneplain character of the surface of the Piedmont Plateau proves the greater age of this region because the peneplain was being produced by wearing off the very materials which were deposited in the adjacent ocean to produce what are now called the Coastal Plain deposits.

6. *By diastrophism.* According to Chamberlin,[1] the great deformations of the earth's crust have been of periodic occurrence. Each great movement has "tended toward the rejuvenation of the continents and toward the firmer establishment of the great (oceanic) basins." Between any two great diastrophic movements there has been a time of quiescence when the base-leveling processes have more or less lowered the continents. Such "base-leveling of the land means contemporaneous filling of the sea

[1] T. C. Chamberlin: Diastrophism the Ultimate Basis of Correlation, in *Jour. Geol.*, Vol. 17, 1909, pp 685–693.

basins by transferred matter" with resultant encroachment of the sea over the land "essentially contemporaneous the world over," which in turn implies "a homologous series of deposits the world over." Thus the times of great diastrophism (recognized by great unconformities and overlapping deposits) should form the basis for separating and correlating at least the larger groups, or even systems, of strata in the earth's crust.

II. PALEONTOLOGICAL (BIOLOGICAL) CRITERIA. The significance of fossils in the determination of geological chronology has already been discussed, but it should here be repeated for emphasis that "order of superposition" of the strata, studied in connection with their fossil content, furnishes the general standard for building up a geological chronology, and affords the best basis for the correlation of formations. In fact, for correlation of formations in distant portions of a continent, or different continents, paleontological criteria alone are satisfactory.

1. *Identity of species.* This is an extremely important method of correlation, especially when species with wide geographic distribution and short geologic range are employed. It is not wise to depend upon a single species for the correlation of far distant formations, because then the time necessary for the migration of the species must be considered. This seldom gives trouble because the geologist usually deals with a number of rapid-moving species In a restricted area, where formations are to be correlated, the same organisms may have continued for a long time, but nearly always some peculiar species furnishes the clew.

2. *Aggregations of forms.* When groups of strata in different areas carry similar aggregations of similar forms, the groups of strata may be safely correlated. Even though a small percentage of the species vary, the method still holds because such variations are to be expected on account of migratory and geographic conditions.

3. *Stage in the evolution of organisms.* Since there has been a gradual development of life with increasing complexity throughout geologic time, the stage of development or evolution shown by the fossils in a group of strata will serve as a basis for general correlation at least. Each era, or even period, shows a characteristic stage of evolution of forms.

4. *Percentage of living species.* This applies only to rock formations of later geologic time, because the older rocks contain no

species like those now living. The percentage of living species becomes greater and greater as the present is approached, and on this basis Lyell subdivided a late period (Tertiary) into three epochs.

In any correlation problem the geologist strives to use as many of the above criteria as possible, the certainty of the correlation being more firmly established when several geological and paleontological criteria are used together.

Significance of Unconformities

Thus far our discussion has been based largely upon the assumption of conformable strata, but many times the succession of strata (so-called "section") under study shows one or more unconformities. An unconformity represents an interruption in the stratigraphic succession. It is nearly always an erosional surface separating two sets of rocks. Rarely, however, it may represent a time of almost complete non-deposition of strata in a submerged area.

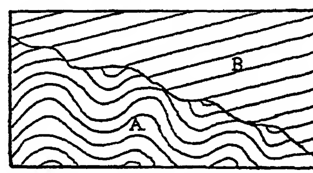

Fig 18

Diagram to illustrate the significance of unconformities. The lower strata (*A*) were folded, raised above water, eroded and then submerged, after which the upper strata (*B*) were deposited and then tilted (W. J M)

In a typical case, after a pile of strata has accumulated to a certain depth in a given region, an emergence, usually due to diastrophism, may take place, resulting in a removal of part of the pile of strata by erosion. The emergence generally involves uplift, often accompanied by folding or tilting, but the pile may remain horizontal or nearly so. Then, due to submergence, newer strata may be deposited upon the eroded surface of the remaining older rocks (Fig. 18). The surface of erosion separating the newer from the older set of rocks is called an unconformity.

It should not be presumed that unconformities exist only in stratified series. Thus, among other cases, there may be an unconformity between either igneous or metamorphic rocks and ordinary strata.

In the case of an obvious unconformity, where the upper strata lie upon the eroded surface of tilted or folded strata, or

of igneous or metamorphic rocks, the term "non-conformity" is applied (Fig. 18). If, however, two sets of strata, separated by an erosional surface, have their stratification practically parallel, the term "disconformity" is applied.

From the above considerations, it is evident that an unconformity signifies a gap or break in the geological record at the locality concerned, that is an absence of both the strata and the fossil record representing a greater or less length of geological time. The missing records for a given region can, however, generally be found by going to some other locality where deposition of sediments was not interrupted at the time when the unconformity was being produced.

Without the aid of fossils, in the ordinary case of unconformity, we could tell that the land emerged above water, was eroded, and again submerged, but we could not tell how much time was involved (Fig. 18). But by noting the fossils in the youngest strata just below the eroded surface, and in the oldest strata just above it, we could tell what epochs or periods the unconformity represents by a comparison with the standard geologic divisions of the world (see table near the close of this chapter).

Because the fossils immediately above and below the line of a profound unconformity show such marked differences, the earlier geologists were misled into thinking that each great unconformity signified an awful catastrophe (physical and organic) which devastated the earth and destroyed all organisms, after which came a period of tranquillity when a new set of organisms was created. This has been called the doctrine of catastrophism. In opposition to this view Sir C. Lyell promulgated the doctrine of uniformitarianism which holds that the evolution of the earth and its inhabitants has progressed practically uniformly, and that missing records in one place are to be found in other places. Today Lyell's view is generally accepted with the modification that times of comparatively more rapid earth disturbance, and probably changes in organisms, have occurred.

Classification of Earth Crust Movements

Irrespective of any theory we may hold in regard to the origin of the earth, there is overwhelming evidence that our planet has been, for long geological ages, a heterogeneous shrinking

body. Among the evidences are the following: profound folding of belts of the earth's crust (orogeny); broad uplifts and warpings of the earth's crust (epeirogeny); and general more or less periodic sinking of oceanic areas, all of which have occurred at various times and in many places.

In 1923, Schuchert,[1] modifying Le Conte's views of 1897, stated "that of crustal movements there are four categories as follows:

"(1) The most primitive, extensive, and longest-enduring progressive movements are those of (a) negative or downward direction, resulting in the oceanic depressions with the heavier kinds of rocks; and (b) positive or upward direction, giving rise to the continental platforms of lighter materials.

"(2) The comparatively quick orogenic progressive movements in one general direction due to crustal lateral thrusting. They give rise in the stratosphere to the folded mountains (orogeny), and in compensating areas to stretching and rifting. Earth shrinkage is concentrated in the main upon the geosynclinal areas, the lines of greatest weakness in the crust.

"(3) The slowly forming epeirogenic or more or less wide and high arching or vertical movements of an oscillating character, now upward and now downward. Epeirogenesis predicates eventual orogenesis

"(4) The isostatic oscillatory movements in compensation for the transfer of load from one place to another; areas of sedimentation tend to sink, and eroding ones rise. Isostasy is an important cause of crustal movement, but is of secondary import to those produced by earth shrinkage."

Significance of Geosynclines

A relatively long, large subsiding downwarp or trough in which sediments accumulate to great depth during a long geological time is called a geosyncline. The sediments are generally of marine origin. In order of magnitude, geosynclines usually range from 100 to several hundred miles in width, and from several hundred to several thousand miles in length.

A typical geosyncline generally lasts through at least several geological periods, and sediments pile up in it to a depth of many

[1] C. Schuchert: *Bul Geol. Soc America,* Vol 34, 1923, pp. 211–212.

thousands of feet — commonly 20,000 to 50,000 feet. Since the strata are of shallow-water origin as proved by coarseness of grain of much of the material, character of the fossils, ripple marks, mud cracks, etc., and since they pile up to such a great thickness, it is obvious that the floor upon which the sediments accumulate must subside more or less gradually during the process of deposition, and at about the rate of deposition

The finest large-scale examples of geosynclines in the history of North America were the Cordilleran trough extending 3000 miles across the western part of the continent, and the Appalachian trough extending 2500 miles across the eastern part of the continent as shown by Fig. 138 Each of these lasted through most of Paleozoic time.

A remarkable fact is that, after long subsidence, a typical geosynclinal basin loaded with sediment is subjected to pressure at right angles to the axis of the trough, and folded and raised into a mountain range. This is because such a geosyncline marks a zone of exceptional weakness in the crust of the earth.

Transgressions and Retrogressions of the Sea

During our study of the clearly recorded portion of the earth's history we shall find positive evidence of repeated transgressions and retrogressions of marine waters over various portions of what are now the continental areas. It is believed that such continental seas were comparatively shallow, that is rarely as much as 1000 feet deep. Since subsidences or elevations of the lands are not the only known causes of sea transgressions and retrogressions, we shall, in the following pages, refer to submergences and emergences of the lands unless there is good evidence for more specific statement in any case.

Submergence may be caused either by (1) sinking of the land; (2) rise of the sea, or (3) both together. "Both the lowering of the land and the rise of the sea may be due to gradation, to diastrophism, or to the two combined. Gradation is perpetual and inevitable where land and sea exist. . . . It has been computed that if the earth, in its present condition, were to remain without deformation long enough for the continents to be base-leveled, the deposition of the sediments thus derived in the sea would raise the sea-level about 650 feet. This would submerge a large part of

the base-leveled land. . . . Base-leveling implies a nearly undisturbed attitude of the land and sea, and hence in itself favors the view that no great deformation affected the continent while it was going on."[1] Much submergence of lowlands would take place long before such widespread base-leveling had been accomplished. Sinking of the land (see below) would of course cause submergence, but whether submergence of the land, in any given case, has been due only or largely to sinking or gradation or to both is at present often difficult or impossible to determine, though it is quite certain that both processes have often been operative.

Emergence may be caused either by (1) rise of the land; (2) lowering of the sea; or (3) both combined. Except rather locally as in the cases of mountain-making (orogenic) movements, it seems doubtful if there is any good evidence for very considerable actual uplifts of extensive land areas thus causing great sea retrogressions. On the other hand, the earth is certainly a contracting body with its whole surface approaching nearer and nearer to its centre. It appears that "the rigidity of the earth may be such that its outer parts are able to withstand for a time the strain set up by contraction. As the strain accumulates, it ultimately overcomes the resistance, and the outer part of the earth yields. If the yielding results in the sinking of the ocean basin, the surface of the water is drawn down, and the surrounding lands seem to rise, unless they sink as much as the surface of the sea does at the same time. The lowering of the sea surface, because of the sinking of the sea-bottom, is probably the most fundamental single cause of the apparent rise of the land. The periodic emergences of the continents, alternating with periodic submergences in the course of geological history, are perhaps to be thus explained. Periodic submergences, on the other hand, might be explained by the sinking of the continental segments of the earth, or by such sinking combined with the processes already referred to which cause the rise of the sea."[2]

The idea of periodic or rhythmic recurrence of diastrophic forces and events has become an important tenet of historical geology. It seems to have been a rule that times of activity — often very widespread — have alternated with times of quiescence. This is strikingly illustrated, as we shall learn, by the advances and retreats of marine waters over large parts of North America

[1] Chamberlin and Salisbury: *College Geology*, p. 479.

[2] R. D. Salisbury: *Physiography, Advanced Course*, pp. 401–402.

during the Paleozoic era. The most profound times of diastrophism, causing widespread emergence of land or great mountain-making, mark the close of the geologic eras, while lesser times of activity usually mark the close of the periods.

Geological Maps and Sections

A geological map shows the areal or surface distribution of rock formations or sets of formations. Such a map usually shows

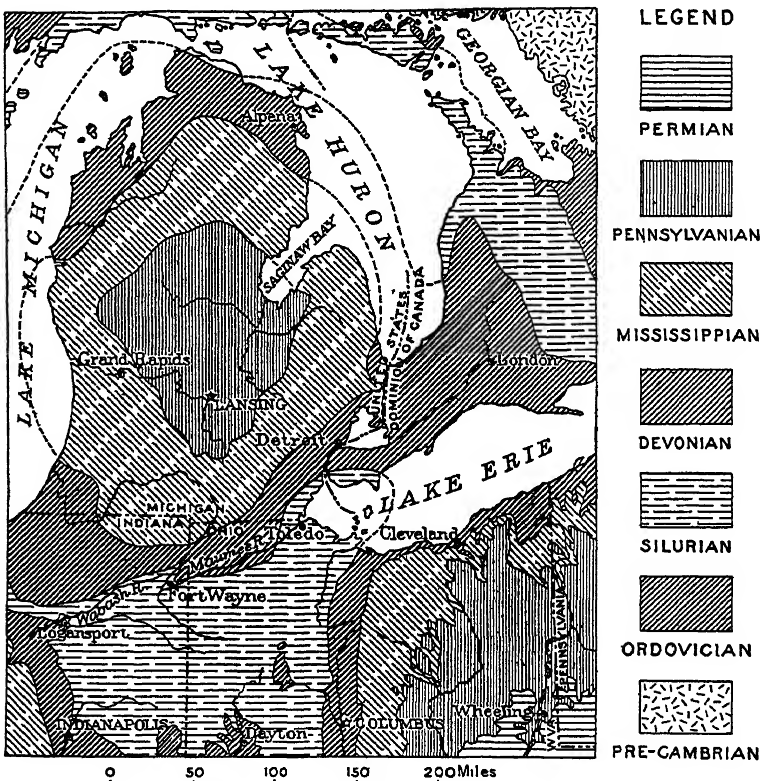

Fig. 19

Geologic map of the Great Lakes region showing the distribution of the rock systems at the surface, disregarding the soil which covers much of the bed rock (After U S Geological Survey)

the areas of bed-rock formations as they would appear at the surface, were there no superficial covering of loose, incoherent materials, such as soils, swamp deposits, etc. The superficial materials may be represented on a separate map, or by means of a special over-color or pattern on the bed-rock map (Fig. 19).

The distribution of each formation or set of formations is represented on the map by a certain color or pattern. At the

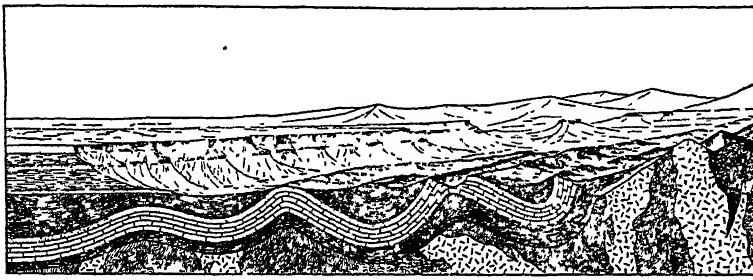

Fig 20

Sketch map showing a structure section at the front, and a landscape beyond. (After U S. Geological Survey)

border of the map there is a so-called legend which is an explanation of the colors or patterns (Fig. 19). In the legend the various formations or sets of formations are arranged in regular order of age, with the oldest at the bottom. In many cases the surface distribution of formations, as shown on a geological map, gives no real indication of the actual extent of the formations in the crust of the earth. Thus extensive formations which have been notably tilted or folded may appear as only narrow belts at the surface (Fig. 20).

"In cliffs, canyons, shafts, and other natural and artificial cuttings the relations of the different beds to one another may be seen. Any cutting that exhibits those relations is called a section, and the same term is applied to a diagram representing the relations. The arrangement of the rocks in the earth is the earth's structure, and a section exhibiting this arrangement is called a structure section. Knowing the manner of formation of rocks, and having traced out the relations among the beds on the surface, the geologist can infer their relative posi-

ions after they pass beneath the surface, and he can draw sections representing the structure to a considerable depth. Such a section is illustrated in Fig. 20. The kinds of rock are indicated by appropriate patterns of lines, dots, and dashes. These patterns admit of much variation, but those shown in Fig. 21 are used to represent the commoner kinds of rock." (U. S. Geological Survey.)

A brief history of the main geological events recorded in their

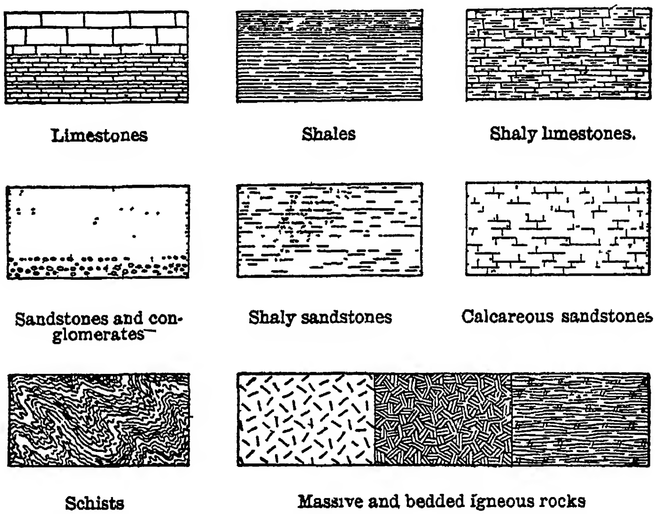

Fig. 21

Symbols used to represent common kinds of rocks
(After U S Geological Survey)

order of occurrence in the structure section (Fig. 20) is as follows: Deposition of the original material of the schist, metamorphism and folding of the schist, intrusion of the igneous masses, profound erosion, deposition of shale and limestone upon the eroded surface, folding of the rocks especially well shown by the shale and limestone, a second interval of erosion, deposition of shale and sandstone upon the second eroded surface, uplift without deformation, and erosion producing the present-day landscape.

A columnar section contains a concise description of the for-

mations which occur in a large or small area as they would appear if all piled up in one locality in order of age and in undisturbed condition Such a section involves a columnar diagram which shows the kinds and order of superposition of the formations, and data on either side of the diagram opposite each formation giving its thickness, description, age, and usually its name (e.g. Fig. 111). Original structures, such as unconformities, are often shown, but subsequent structures, such as folds and faults, are seldom represented.

Paleogeography

Paleogeography literally means "ancient geography" and deals with the geographic conditions of the earth during geologic time. In making a paleogeographic map to represent North America at a given time in its history, the attempt is made to show the relations of lands and waters, sometimes with distinctions between areas of marine and of continental deposition, location of highlands, etc. Until quite recent years there were only crude attempts at making such maps for North America, for the knowledge of the continent was not sufficient to form a reasonable basis upon which to work. Within the last twenty years, however, several sets of paleogeographic maps, notably those by Bailey Willis [1] and Charles Schuchert,[2] have been prepared. The maps used in this text are in the main based upon data (somewhat modified) from both the Willis and the Schuchert maps. The Schuchert maps are more numerous and detailed.

Willis gives a general statement of the lines of evidence used in the construction of his maps as follows: "A certain period having been selected as that which should be mapped, the epicontinental strata pertaining to that time interval have been delineated. The phenomena of sedimentation and erosion have then been correlated, with a view to determining the sources of sediment and topographic conditions of land areas and from these data the probable positions of lands have been more or less definitely inferred. Thus, certain areas within the continental margin are distinguished as land or sea, and these areas may be defined as separate bodies or connected according to inferences based upon isolated occurrences

[1] B. Willis: *Jour. Geol*, Vol 17, 1909.

[2] C. Schuchert: *Bul Geol Soc. America*, Vol 20, 1910; also *Text-book of Historical Geology*, 1924

or upon later effects of erosion. It is assumed that the great oceanic basins and such deeps as the Gulf of Mexico and Caribbean have been permanent features of the earth's surface at least since some time in the pre-Cambrian . . .

"From the geographic conditions thus developed, inferences regarding the climate and the life habitats of the time may be drawn. If now we turn to the records of paleontology, and compare the distribution of faunas and floras [1] with the conditions of distribution which should result from the inferred physical phenomena, we may check the whole line of reasoning and by a readjustment draw a step nearer to the truth. This is the method which has been pursued in making the maps of North America." [2]

It should be borne in mind that such paleogeographic maps are generalized and rather tentative as regards many details — generalized because each map represents a considerable time period so that certain more local geographic changes during the period are not indicated, and tentative because of lack of knowledge concerning many areas and lack of certainty in the correlation of formations in certain other areas. With progress in knowledge of the strata, less generalized and more accurate maps will be made. Nevertheless the series of maps used in this text will serve to give the beginner a very good idea of the broader features in the geographic development of our continent.

Classification of Geologic Time

We have already shown how, by employing the law of superposition of the strata together with the law of included fossils, the rock formations of various parts of the earth may be correlated and built up according to their natural order of age into a standard for comparison or a geologic column. The subdivisions of the geologic column represent the times when the successive rock formations were deposited. Different names have, from time to time, been assigned to these divisions, and these names are in more or less general use.

[1] The term "fauna" refers to an assemblage of animals populating a given area during a certain epoch In a similar sense the term "flora" is applied to an assemblage of plants

[2] B Willis· *Jour Geol*, Vol 17, 1909, pp 201–202.

For a long time the subdivisions of the geologic column were made almost solely on the basis of marked differences in fossils, but it is now recognized that such differences were, in no small degree, caused by corresponding changes in the environment in which the organisms lived, or, in other words, by changes in the climate, the topography, the relations of land and sea, etc. So we now try to divide the geologic record at the points where the revolutionary physical changes are indicated, and to make corresponding divisions of geologic time itself. Thus there are two kinds of divisions — one for the rocks themselves, and the other for the time represented by the rocks.

The following time and rock scales have been adopted by the International Geological Congress. Immediately following these scales, there is presented the table of main geological divisions as now recognized in North America.

Time scale	*Rock scale*
Era	Group
Period	System
Epoch	Series
Age	Stage

TABLE OF MAIN GEOLOGICAL DIVISIONS

Era and group	*Period and system*
CENOZOIC	Quaternary Tertiary
MESOZOIC	Cretaceous. Jurassic. Triassic.
PALEOZOIC	Permian. Pennsylvanian (Upper Carboniferous). Mississippian (Lower Carboniferous). Devonian. Silurian Ordovician. Cambrian.
PROTEROZOIC	Keweenawan.[1] Huronian.
ARCHEOZOIC	Archean.

[1] The terms "Keweenawan" and "Huronian" apply only to the Great Lakes region.

The names of eras follow a definite plan depending upon the great life stages. Thus Archeozoic means literally "primitive or beginning life"; Proterozoic means "earlier or less primitive life"; Paleozoic means "ancient life"; Mesozoic means "intermediate life"; and Cenozoic means "recent life." The period names do not follow such a definite plan of nomenclature, various ideas being represented. These names will be explained when the different periods are taken up for discussion.

Length of Geological Time

How old are the Archeozoic rocks? If we attempt to answer this question in terms of years we encounter real difficulties, there being no definitely established exact standard for such measurement or comparison. In any case the time is utterly inconceivable to us, the important thing to bear in mind being that the great events of well-known earth-history which have transpired since the formation of the oldest known Archeozoic rocks have required a lapse of at least scores of millions of years. Among such events have been the long, slow, generally progressive evolution of life; the enormous accumulations of sediments at many times and places; the repeated advances and retreats of the sea over many parts of the continents; the building up and wearing away of mountain ranges at many times and places; as well as various other profound changes which have affected the face of the earth. On the basis of such geological happenings, an exceedingly conservative minimum estimate of the age of the Archeozoic rocks is 100,000,000 years.

Measurements of time on the basis of radioactivity run much higher. In radioactivity a chemical element of higher atomic weight is transformed into one of lower weight. Thus uranium changes through successive stages of radium into a certain type of lead. The rate of this change is said to be rather accurately known, so that the determination of the amount of the special type of lead in minerals containing uranium affords a means of ascertaining at least approximately the time when the transformation started. Based upon this principle, an age of considerably more than a billion years has been assigned to the Archeozoic rocks; the Paleozoic era opened more than 500,000,000 years ago; the Mesozoic era nearly 200,000,000 years ago; and the Cenozoic era at least 50,000,000 years ago.

Comparison of Human and Geologic History

One of the most striking differences between human and geologic history is the extreme brevity of the one as compared with the vast time represented by the other. Human history is to be measured by some thousands of years, while geologic history must be measured by at least scores of millions of years. A recent event, geologically speaking, like that of the building of the Coast Range Mountains, or the carving out of a tremendous canyon like the Grand Canyon of the Colorado in Arizona, required some hundreds of thousands, if not a few millions, of years. Human history is roughly divided into certain ages according to the predominant influence of some person, nation, principle, or force. Thus we speak of the "Age of Pericles," the "Roman Period," the "Age of the French Revolution," or the "Age of Electricity." Geologic history is subdivided according to great predominant physical or organic phenomena as, for example, the "Appalachian Revolution" (toward the close of the Paleozoic era), the "Rocky Mountain Revolution" (toward the close of the Mesozoic era), the "Age of Fishes" (Devonian period), the "Age of Mammals" (Cenozoic era).

Students of earth history, like students of human history, must be very careful to make a distinction between events and records of events, because by no means all historical events are recorded. Events are continuous, while their records are usually much interrupted and apparently sharply separated from each other. In both geologic and human history, times or periods of comparatively quiet and slow change have often given way to times of comparatively rapid, to even revolutionary, change.

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CHAPTER III

ORIGIN AND PRE-GEOLOGIC HISTORY OF THE EARTH

IF we define geology as the study of the history of the earth and its inhabitants as revealed in the rocks, it is evident that the problems of the origin and very early development of the earth are strictly astronomic rather than geologic. It is generally agreed that geological history did not begin till the ordinary earth processes, such as weathering and erosion, transportation and deposition of sediments, etc., began to operate. Since, however, the pre-geologic condition of the earth must have gradually given way to its geologic condition, it is a matter of interest for the geologist to consider the hypotheses regarding the very early development of the earth.

THE SOLAR SYSTEM

The sun has a diameter of about 866,000 miles, and a volume 1,300,000 times that of the earth. Around this central sun eight planets — Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune — revolve in nearly circular orbits. Three of these planets — Mercury, Venus, and Mars — are smaller than the earth, while the others are larger, Jupiter being 1,300 times as large. The earth is about 93,000,000 miles from the sun and requires one year for a trip in its orbit around the sun, while Neptune, the most distant planet, is about 2,800,000,000 miles from the sun and requires 164 years for a revolution about the sun. Each planet also rotates upon its axis, the earth accomplishing a rotation every twenty-four hours. Most of the planets have smaller bodies called satellites or moons revolving about them, such as Earth with its one moon, Saturn with eight moons, etc. The sun and the eight planets with their satellites, together with a group of many small independently revolving bodies called "planetoids," comprise the solar system. That this solar system constitutes only a very small part of the universe is clearly proved by the fact that the nearest fixed star is several trillions of miles from the earth.

Some of the well-known facts which any hypothesis of the origin of the solar system must explain are as follows: (1) The planet orbits are all elliptical, but nearly circular; (2) the orbits lie in nearly the same plane; (3) all planets revolve about the sun in the same direction; (4) the sun's direction of rotation is the same as that of the planets' révolution; (5) the planes of the planets' rotation nearly coincide with the planes of their orbits (except Uranus and Neptune); (6) the direction of the planets' rotation is the same as that of their revolution; and (7) the satellites revolve in the direction of rotation of their planets (two or three exceptions).

Hypotheses of Earth Origin

Nebular or Ring Hypothesis.—In 1796 Laplace published a remarkable work on astronomy, and in its last chapter he put forth his now well-known hypothesis regarding the origin of the solar system. He postulated a spheroidal mass of very highly heated, incandescent gas or nebula greater in diameter than the present solar system, this whole mass rotating in the direction of the revolution of the existing planets. Due to loss of heat by radiation, this mass contracted and its shrinkage necessarily made it rotate more rapidly upon its axis, at the same time causing the centrifugal force on its outside to become stronger and stronger. Finally the centrifugal force at the equator became equal to the force of gravity and the equatorial portion was left off (not thrown off) as a ring surrounding the contracting remainder. The materials of the ring condensed to form the outermost planet. By continued contraction of the rotating nebula, the other rings and planets were formed. The satellites were produced in a similar manner by rings left off by the shrinking planets.

Briefly, according to this hypothesis, the earth was originally highly heated and much larger than now. During its cooling and contraction, its original hot and dense atmosphere, which contained all the earth's water in the form of vapor, gradually became thinner due to absorption by the earth. When the conditions of pressure and temperature were favorable, water vapor condensed to form the hydrosphere. The oldest rocks must have been igneous, that is they were portions of the original crust formed by cooling of the molten globe.

For over a hundred years the Laplacian hypothesis has exerted

a profound influence upon science, philosophy, and theology, and certainly many of the important phenomena of the solar system are explained by it. Some serious objections to it may, however, be briefly stated as follows: (1) Nearly all existing nebulas are spiral and not circular; (2) spectroscopic study shows that these nebulas do not consist of gas, but rather of discrete liquid or solid particles; (3) the backward revolutions of certain satellites oppose the hypothesis; (4) rings could not have been left off, that is there could have been no intermittent process of the sort; and (5) it is not at all clear how the matter of the rings could have condensed into planets.

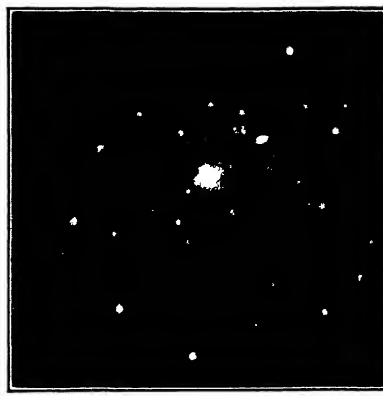


Fig. 22

A very symmetrical spiral nebula in Pisces (M 74). Photo by Lick Observatory. (From Chamberlin and Salisbury's "Geology," permission of Henry Holt and Company.)

Planetesimal or Spiral Hypothesis.—It is a remarkable fact that, although many thousands of nebulas are known, there are very few examples of ring nebulas of the Laplacian type among them. Spiral forms are very common, especially the smaller ones. Also, as above stated, spectroscopic study of these nebulas shows them to be made up of discrete (liquid or solid) particles rather than of gas. The Planetesimal hypothesis,[1] formulated by Chamberlin and Moulton, "postulates that the matter of which the sun and the planets are composed was, at a previous stage of its evolution, in the form of a great spiral swarm of discrete particles whose positions and motions were dependent upon their mutual gravitation and their velocities" (Moulton). A nebula of this sort comprised a luminous central mass (the future sun) from the opposite sides of which two luminous spiral arms streamed out with occasional larger masses or knots along each arm, and with dark lanes between the arms (see Fig. 22). Also some nebulous

[1] An elaborate discussion of this hypothesis may be found in Chamberlin and Salisbury's Geology, Vol. 2.

matter occupied the spaces between the arms. Such a distribution of matter in a spiral shows that the form could not have been maintained by gaseous pressure, as in the Laplacian hypothesis, but rather by the movements of the separate particles or masses. Since these particles are thought to have moved like miniature planets, they are called planetesimals. Each planetesimal is considered to have moved in its own orbit around the central mass The planetesimals did not move along the arms of the spiral, but rather crossed them at considerable angles (Fig. 23). "When we see a spiral we do not see the paths which the separate masses have described, but the positions which they occupy at the time. In the present case (Fig. 23) if a smooth curve is drawn through the regions where the matter is densest, it will form a sort of double spiral as represented by the full lines" (Moulton) The dotted lines in the figure represent orbits of some of the particles or knots. Due largely to crossing of orbits, the knots increased in size by a gathering in or accretion of the planetesimals. Meteors, which now strike the earth, are thought to be planetesimals still gathering in, though very slowly at present. The spiral orbits of the knots (planets) gradually gave way to the elliptical orbits due to a sort of wrapping up process around the central attracting body (sun).

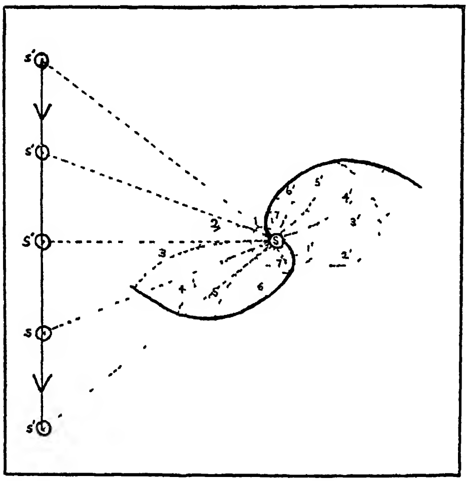


Fig 23

Diagram to illustrate the formation of a spiral nebula, S, sun, S', passing star whose direction of motion is indicated by the arrows The numbered dotted lines show the paths followed by masses pulled out from S by S'. The straight dotted lines are paths which the disrupted masses would have followed had S' remained stationary in the respective positions indicated (Modified after Moulton by W J. M)

The origin of the spiral is suggested as having been due to the disrupting influence of the central body or sun by a passing star, the disrupted particles or masses at first moving straight toward the passing star, but, because of change in position of the passing body, the disrupted masses gradually became pulled around and their paths curved into spirals as shown in Fig. 23. In accordance with the principle of the well-known tide producing force, similar disrupted masses must also have shot out from the opposite side of the sun or central body. Finally when the passing star had so far gone by as to have largely lost its power of effectively attracting the sun, the spiral orbits of the planetesimals gradually became coiled into elliptical or nearly circular orbits around the sun.

Briefly, according to this hypothesis, the earth was never a highly heated gas and never necessarily more highly heated than at present, hence sedimentary as well as igneous materials may well be expected among the earliest formed rocks. Instead of a much larger original earth, it increased in size by accretion of planetesimals. With increase in size came increase in force of gravity, causing compression of the earth's matter and generation of more and more interior heat. Accompanying this increasing pressure and heat, gases (including water vapor) were driven out to form an atmosphere which gradually became larger and denser. When the water vapor had sufficiently accumulated, precipitation resulted to initiate the hydrosphere.

TABULAR SUMMARY OF STAGES OF THE EARTH'S HISTORY[1]

9. Cenozoic era 8. Mesozoic era 7 Paleozoic era 6 Proterozoic era	Sedimentation predominant over vulcanism. Higher forms of organisms.
5. Archeozoic era	Vulcanism predominant over sedimentation. Either initial or at least only very simple organisms.

Nebular hypothesis	*Planetesimal hypothesis*
4 Hydrospheric (oceanic) stage.	Initial hydrospheric (oceanic) stage.
3. Lithic (congelation) stage.	Initial volcanic stage.
2 Molten stage.	Initial atmospheric stage.
1. Nebular (gaseous) stage.	Nuclear (non-gaseous) stage.

[1] Modified after Chamberlin and Salisbury.

CHAPTER IV

THE ARCHEOZOIC ERA

The Oldest Known Geologic Records. — In earth history, as in human history, the recorded events of earliest times are fewest and most obscure, and hence the least intelligible of all. In spite of a certain disadvantage in beginning with the least known part of the history of the earth, the only satisfactory method of presenting the subject is "to follow the natural order of events. This has the great advantage of bringing out the philosophy of the history — the law of evolution" (J. Le Conte). The earliest known geologic history is recorded in the rocks of the Archean system. While it is true that the most obscure records of any rock system are here, partly because the original structures of these rocks have generally been so profoundly changed (metamorphosed) and partly because of the almost complete absence of well-defined fossil forms, nevertheless, certain very important conclusions regarding the earliest known era of geologic time may be reached through a study of the rocks of the Archean system. The present state of our knowledge does not warrant the subdivision of the Archeozoic into two or more definite periods or systems.

General Character and Origin of the Archean Rocks.—"Archean Complex," "Basal Complex," "Fundamental Complex," etc., are all terms which have been applied to the rocks of the Archean system which invariably occupy a basal position with reference to all other rock systems. "The Archean system is a crystalline complex beneath the base of the determined sedimentary succession. . . . The United States Geological Survey has restricted the term to a complex of basic and acidic surface and deep-seated igneous rocks, of schists and gneisses in part derived from them and in part of unknown origin, and of shreds and small masses of metamorphosed sediments, all unconformably below and older than the Algonkian sedimentary rocks, which are the lowest series in which ordinary stratigraphic methods have been applied. Their litho-

logical variations are many. . . . The Archean as a whole is homogeneous in its heterogeneity."[1]

Briefly stated, the Archean system exhibits the following characteristics: (1) So far as observed, it always shows a profound unconformity or erosion surface at its summit; (2) its lower limit or base has never been determined, and is likely inaccessible; (3) its thickness is very great, at least tens of thousands of feet, and possibly many miles, (4) its rocks are always crystalline and usually highly metamorphosed and tilted or folded; (5) it comprises a most heterogeneous group of rocks, often intimately associated, such as lavas and tuffs; shales, sandstones, and limestones which have been highly metamorphosed to schists and gneisses, quartzites, and marbles; some beds of iron ore; and great volumes of granite or granitic gneisses; (6) almost invariably igneous rocks (granites or lavas) greatly predominate; (7) it rarely, if ever, contains distinct fossils, though certain evidences of life do exist; and (8) so far as known it is universally present at or under the earth's surface.

The Archean has been more or less studied in various countries, and the above named features always appear to characterize it. Caution must be exercised, however, in assigning groups of rocks in different regions to the Archean merely because they present some or many of these characteristics. Many rocks formerly classed with the Archean have been proved to be of later age. If rocks with all the characteristics of Archean lie below definitely determined (by fossils) Cambrian strata, and are separated from the Cambrian by a great series of sedimentary or metamorphic rocks (Proterozoic), then we may be fairly certain that the rocks belong to the Archean system. If crystalline rocks of Archean appearance are directly overlaid by Cambrian strata, or by Mesozoic strata, the crystalline rocks in the first instance may be either Archeozoic or Proterozoic, and in the second instance of any age preceding the Mesozoic era.

Subdivisions of the Archean System.—Wherever studied the Archean appears to be separable into two rather distinct groups or classes of rocks, namely, (1) a volcanic and sedimentary series, and (2) a plutonic series.

The volcanic and sedimentary series is largely composed of metamorphosed lava flows and volcanic tuffs; some massive igne-

[1] Van Hise and Leith: *U. S. Geol. Survey Bull.*, 360, p. 26.

ous rocks; and more or less schist, gneiss, quartzite, marble, and some iron ore, representing all the common types of sedimentary rocks in a highly metamorphosed condition. In the Lake Superior district this series is called the Keewatin, and in eastern Canada and the Adirondacks the Grenville.

The Keewatin is essentially a metamorphosed volcanic series of lavas and tuffs associated with minor amounts of metamorphosed strata, mainly black slates and schists. The thickness of the Keewatin (both volcanic and sedimentary) varies from several thousand feet to over 20,000 feet. It outcrops over a wide area.

The Coutchiching is a very ancient sedimentary series which has been metamorphosed into mica schist. In Canada, a little west of Lake Superior, it is said to be several thousand feet thick. Its exact relation to the Keewatin is still a problem. In any case it is very closely related to, and seemingly conformable with, the Keewatin.

On the north side of Lake Huron, the oldest Archeozoic rocks seem to be schists, representing mainly metamorphosed volcanic rocks. Resting upon the schist is a great, widespread, sedimentary series, thousands of feet thick, made up largely of quartzites, slates, and schists. This so-called Sudbury series is of pre-Huronian age and, therefore, probably best to be regarded as of Archeozoic age.

The Grenville is widespread in southeastern Ontario, southern Quebec, and the Adirondack Mountains of northern New York. It is essentially a sedimentary series many thousands of feet thick (maximum, possibly 90,000 feet), consisting largely of schists, quartzites, and crystalline limestones representing highly metamorphosed shales, sandstones, and limestones. Some altered igneous rocks seem to be contemporaneous with the strata. "The Grenville strata have been so profoundly changed from their original condition that certain of the highly sedimentary features have been completely obliterated. Thus the absence of water-worn particles and fossil shells, both of which are so characteristic of ordinary strata, is due to complete crystallization (metamorphism) of the Grenville strata since their deposition. There are, however, certain proofs of the sedimentary origin of the Grenville. The fact that these rocks commonly occur in alternating layers, which stand out in sharp contrast because of marked differences in composition and color, furnishes strong evidence

that this distinct banded effect is due to differences in original sedimentation (Fig. 24). A great mass of igneous rock is generally characterized by more or less homogeneity throughout; a mass of typical sediments, on the other hand, is arranged in distinct layers, such as shale, sandstone, or limestone which show frequent differences in composition. In the Grenville there are extensive beds of limestone, and such rocks could not have been of igneous origin. . . . In some places the strata are so filled with graphite flakes that the mineral is mined. Carbon existing under such conditions is doubtless of organic origin and represents (in crystallized form) the final stage in the decomposition of organisms which lived in the waters while the Grenville strata were being deposited"[1]

The plutonic series consists of tremendous masses of deep-seated igneous rocks which are mostly red to gray granites, often of different ages, and at times with more basic syenitic to even gabbroic facies. A most important feature of this series, called the Laurentian in the Lake Superior district and in eastern Canada, is the fact that it is invariably intrusive into the first or lava-sedimentary series. Thus as regards actual position in the earth's crust, the Laurentian rocks generally lie under or within the Keewatin or the Grenville, but since the contact is clearly an intrusive one, the law of superposition cannot here be applied for relative age determination.

The following tabular summary will serve to make clear the subdivisions of the Archeozoic and their relation to the Proterozoic in a portion of North America where the pre-Cambrian rocks have been most carefully studied.

	Lake Superior Region	*Lake Huron Region*[2]
PROTEROZOIC	Huronian (Great unconformity)	Huronian (Great unconformity)
ARCHEOZOIC	Laurentian granite (Intrusive into Keewatin)	Granite (Intrusive into Sudbury)
	Keewatin and Coutchiching (Volcanic and sedimentary)	Sudbury (and Grenville farther east) (Sedimentary) Schist-volcanic complex

[1] W. J. Miller: *The Geological History of New York State*, pp 29–30

[2] Classification according to W. H. Collins, with the exception of the Grenville.

Correlation of Archean Rocks. — Because of the complete absence of satisfactory methods of correlation, pre-Cambrian rocks in one region cannot certainly be regarded as equivalent to those in another region separated from it. Thus the Grenville of eastern Canada cannot at present be certainly correlated with the older pre-Cambrian of the Lake Superior region, though considerable evidence points to such a correlation. If this be true, it is evident that the whole of the Proterozoic is absent from eastern Canada and the Adirondacks, where Upper Cambrian strata rest upon Grenville and Laurentian.

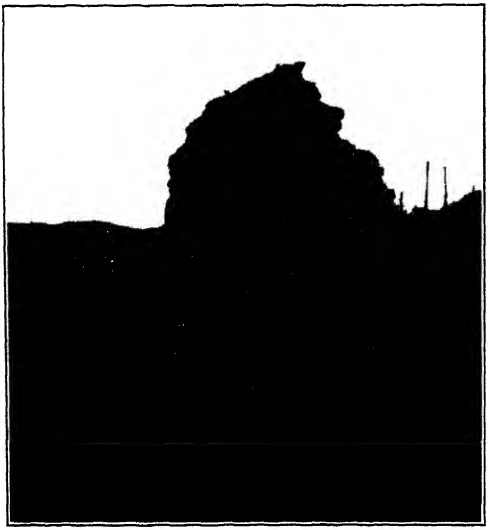


Fig 24

Archean (Grenville) metamorphosed strata in the central Adirondacks Note the distinct stratification. (Photo by the author)

It must be remembered that the Archeozoic represents a vast length of time. In fact the Archeozoic era may have been longer than all subsequent time, particularly if the Planetesimal hypothesis be accepted, because, according to that view, volcanic extrusions with gradually increasing accumulation of sediments might well enough have taken place long before the earth had attained anything like its present size. Realizing the great thickness of rocks and long time which the Archean presents, it scarcely seems probable that its base, or even the base of that portion which carries sediments, is anywhere exposed to view. Bearing these things in mind we also see that though in many regions rocks may be confidently referred to the Archean system, nevertheless, such rocks may really represent vast age differences within that system.

Close of the Archeozoic (Laurentian Revolution). — As already stated, the Keewatin and Grenville series of strata and volcanic rocks have been intruded by great volumes of Archeozoic granite and other plutonic rocks. This is true throughout much of the vast Canadian-Great Lakes area of the Archeozoic rocks. In fact much of the rock of this area consists of this so-called Laurentian granite. Large masses of the granite magma broke into the Keewatin-Grenville series, often more or less intimately penetrating or injecting them, while other large masses cooled and consolidated underneath the older rocks. Great uplift and more or less folding accompanied the magmatic invasion, probably causing the development of more or less well-defined mountain ranges. In the present state of our knowledge, however, we cannot give any details in regard to the size or position of these ranges. Next followed a long interval of profound erosion whereby the region was worn down to a lowland approaching a peneplain.

That the events just mentioned took place before the oldest Proterozoic strata were laid down in the region is amply proved not only by the fact that the more or less tilted and folded Archeozoic strata were deeply cut into and leveled, but also by the fact that the Laurentian granite, which had cooled far below the surface, was extensively laid bare by erosion before the earliest Proterozoic strata were deposited upon the old eroded surface.

Not only in the Canadian region, but wherever the Proterozoic rocks have been found resting upon the Archeozoic, the two sets of rocks are separated by a profound unconformity representing a very long interval of erosion, as for example in the depths of the Grand Canyon of Arizona. Evidently North America stood well above the sea for a long time, and was nearly leveled by erosion, before the oldest known Proterozoic strata were laid down.

Distribution of the Archean. — So far as known, Archean rocks appear to be universally present at or below the earth's surface. If this be true, and all evidence strongly favors such a view, it is a most remarkable characteristic of the Archean, since no other rock system has such a distribution.

A rock formation may be so distributed in the earth's crust as to be present (1) at the surface where mere superficial deposits, such as mantle rock, glacial drift, etc., are disregarded; (2) under

cover of later rocks, but where its presence is certainly known from surface observations, well borings, etc , and (3) under cover of later formations, but where its presence cannot be definitely proved. Considering all regions which have been geologically explored,

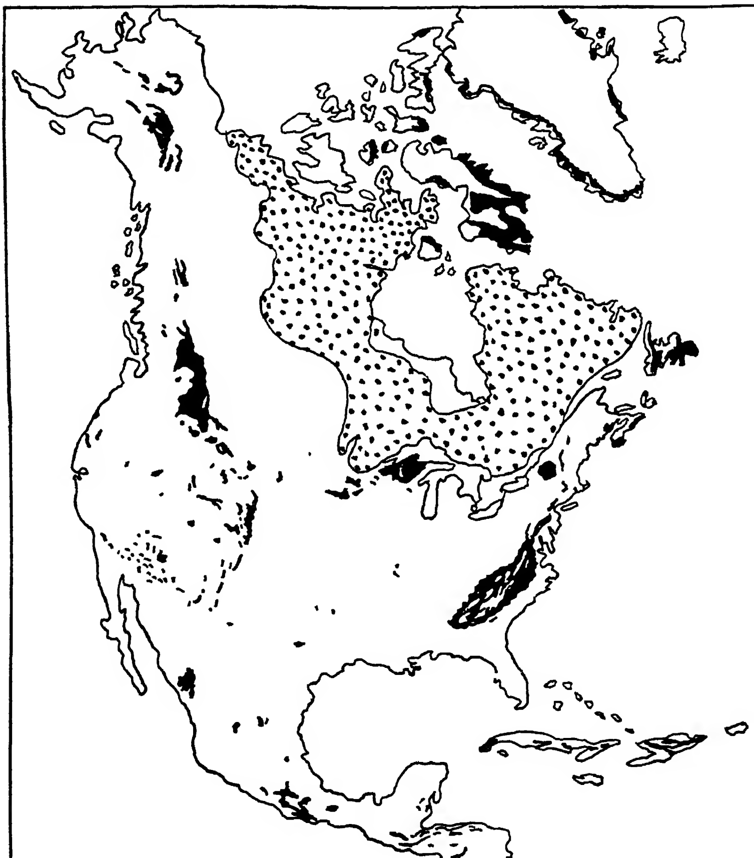


Fig. 25

Map showing the surface distribution of pre-Cambrian (Archeozoic and Proterozoic) rocks in North America Largest area shown by dotted pattern; smaller areas by solid black. (Modified by W. J M. after Willis, U. S. Geological Survey.)

the Archean is estimated to appear at the surface over about one-fifth of the land area of the earth.

On the accompanying map (Fig. 25) the surface distribution only of pre-Cambrian rocks in North America is shown. Most of these areas contain more or less Archean. The map shows the greatest area of pre-Cambrian rocks in North America to be around Hudson Bay. This vast area of fully 2,000,000 square miles consists mostly of Archean. Among the principal smaller areas containing more or less Archean are those of Newfoundland, New England states, Adirondack Mountains, Piedmont Plateau district, Michigan, Wisconsin, Minnesota, and numerous small areas in the Rocky Mountain district (including Alaska) and westward. In drilling deep wells in many places, particularly in the upper Mississippi Valley, rocks of the pre-Cambrian complex have been encountered, and so we may be confident of the presence of Archean under cover of thousands of square miles of later rocks. These facts of distribution, together with the fact that wherever erosion has gone deep enough the Archean never fails, leave little room for doubt concerning the universal presence of the Archean in North America.

Foreign Archean. — Judging by exposures along its borders, Greenland appears to be largely occupied by Archean rocks.

The Highlands of Scotland show one of the most clearly exposed areas of Archean in the world, and detailed studies have shown it to be remarkably like that of the Lake Superior region.

Scandinavia exhibits the largest area of Archean rocks in Europe, and considerable study has shown the rocks to be very similar to those of North America.

Archean rocks are also known in Finland, France, Bavaria, Bohemia, Spain, India, Australia, China, and Japan.

Life and Climate of the Archeozoic Era. — If the term "Archeozoic" is properly applied, rocks of that age should show the earliest evidences of life. Certain beds of graphite; beds of iron ore which were derived from carbonates; the uncommon occurrence of numerous flakes of graphite in certain Archean schists, gneisses, and crystalline limestones; and the very existence of the limestone itself, altogether quite certainly imply the existence of life in Archeozoic time. Limestone has sometimes been of chemical origin, but the presence of clearly bedded graphitic schists and crystalline limestones in a distinct sedimentary series

almost certainly shows the influence of organisms in the production of both the graphite and the limestone.

Fossil forms of low-order single-celled plants (Algæ) have been reported recently from the Archeozoic rocks of Minnesota. With this possible exception, nothing like determinable fossil forms have been found in Archean rocks, and even if such ever were present they must have been almost entirely obliterated by the intense metamorphism to which the rocks have been subjected. In the light of the evolution which took place during much better known geologic time, it is quite certain that the Archeozoic organisms must have been much simpler forms than those of the early Paleozoic which, in turn, were much simpler than those of the present day.

All we can say about Archeozoic climate is that, during some of the time at least, it was favorable for the existence of life and for ordinary geologic processes such as erosion and sedimentation.

Economic Products. — Iron ore in workable beds occurs in the Archean of the Lake Superior district.

Granting the Archean age of the Grenville series, it contains valuable marble deposits as at Gouverneur in northern New York.

Granites intrusive into the Grenville contain rich magnetite deposits in northern New York.

The cobalt and nickel deposits of Ontario, Canada, are, in part at least, associated with Archean rocks.

CHAPTER V

THE PROTEROZOIC ERA

THE Proterozoic era, represented by the Proterozoic group of rocks, includes the time between the Archeozoic and the earliest Paleozoic (Cambrian) period, the Cambrian system comprising the oldest known rock system with abundant fossils.

Great Unconformity between the Archeozoic and Proterozoic Groups. — As already stated, wherever observations have been made under favorable conditions, the summit of the Archean complex appears to be marked by a profound unconformity. Such an unconformity, however, cannot be universal because the very fact of extensive erosion of certain areas implies the deposition of the eroded sediments in other areas. Such sediments, if found, would contain the records of the time interval indicated by the great unconformity. So far at least, this sedimentary record has not been brought to light, probably either because (1) these sediments were deposited in ocean basins not since exposed as dry land; or (2) these sediments are not at present exposed to view because concealed under later formations; or (3) these sediments have not been recognized as such. Also it is not at all unlikely that some or even many of these sedimentary areas may subsequently have become land areas so that, as a result of erosion, more or less of the sediments were again removed to again be deposited as Proterozoic or later sediments. Future researches may bring to light some of the now "lost records" which represent the great unconformity or time gap between the Archeozoic and Proterozoic.

General Character and Origin of the Proterozoic Rocks. — Emphasis should be placed upon the fact that the Proterozoic was the first era during which ordinary processes of weathering, erosion, and deposition of great series of strata became dominant processes, such processes having been dominant ever since. Judging by the records, the Proterozoic, on one hand, was marked by less igneous activity than the Archeozoic, while, on the other hand, it was marked by distinctly more igneous activity than any subsequent

era. In this respect, therefore, the Proterozoic was transitional in character.

"The Algonkian[1] system as this term is used by the United States Geological Survey, includes sedimentary formations and their metamorphosed equivalents with associated igneous rocks beneath the Cambrian and resting upon the Archean complex. It includes the greater part of the sedimentary rocks of pre-Cambrian age and practically all to which present stratigraphic methods have been found to apply, though it contains also sedimentary rocks so deformed and metamorphosed that their stratigraphy is obscure . . . The Algonkian sediments are known to contain a few fossils, representing the earliest forms of (animal) life yet found."

An important feature, especially of the later Proterozoic rocks, is the frequent presence of great series of non-metamorphosed strata which are therefore the oldest known unaltered strata of the geologic column. Such strata include all common types of sedimentary rocks as conglomerates, sandstones, shales, and limestones Basal conglomerates, which were derived from the lands over which the Proterozoic seas at various times spread or transgressed, are frequently found at the bottoms of the great sedimentary series. Other great series of Proterozoic rocks of undoubted sedimentary origin are more or less metamorphosed to schists, quartzites, and crystalline limestones. The earliest Proterozoic sediments were derived from exposed portions of the Archean, while later Proterozoic sediments may have been derived either from exposed Archean or older Proterozoic. That the processes of sedimentation during the Proterozoic era were essentially the same as those of today is clearly proved by the very character of the sediments, the typical stratification to even lamination, shallow-water marks, etc.

Beside the sedimentary deposits, there is much igneous rock both in the forms of intrusions into the sediments and as extrusions or lava-flows. In the latest (Keweenawan) Proterozoic rocks of the Lake Superior district lava flows or beds predominate over sediments, while, in the older Proterozoic, igneous rocks (either intrusive or extrusive) may locally predominate.

[1] The term "Algonkian," referring to an Indian tribe of the Great Lakes region, was for some time, and still often is, applied to the group of rocks now more generally and satisfactorily called Proterozoic

In addition to the frequent metamorphism, the Proterozoic rocks have often been subjected to great deformative movements in the earth's crust so that the rocks have either been tilted or highly folded. Sometimes they have been infolded among the Archean rocks.

Subdivisions of the Proterozoic. — In many regions where detailed studies have been made, the Proterozoic group may be subdivided into from two to four series separated by distinct unconformities. In some places only one series has been recognized. At present no such subdivision into series has a world-wide or even continent-wide application. Generally each of these series shows a thickness of at least a few thousand feet, while the whole Proterozoic group has a maximum thickness of many thousands of feet, or, according to some estimates, at least ten miles in the Lake Superior district. These subdivisions or series of Proterozoic rocks will perhaps be best understood by briefly describing a few of the better known regions.

	Lake Superior Region	*Lake Huron Region*[1]
PALEOZOIC	Cambrian	Ordovician
	Great unconformity	
PROTEROZOIC	Granite (Intrusive into Keweenawan) Keweenawan (Volcanic-sedimentary) (Unconformity)	Killarney granite (Intrusive into Keweenawan) Keweenawan (Igneous) (Unconformity)
	Huronian (Sedimentary) Upper (Animikian) (Unconformity) Middle (Unconformity) Lower	Cobalt (Sedimentary) (Unconformity) Bruce (Sedimentary)
	Great unconformity	
ARCHEOZOIC	Laurentian granite	Granite

Lake Superior District. — One of the best and most carefully studied Proterozoic districts in the world is the western Lake Superior region. Proterozoic rocks are there divided into four dis-

[1] After W. H. Collins.

tinct, largely sedimentary series separated from each other by unconformities, and named Lower Huronian, Middle Huronian, Upper Huronian (Animikian), and Keweenawan (Fig. 26). At some localities not all of these series are represented. The relations of these series to each other and to the Archeozoic below and Paleozoic above are brought out in the accompanying tabular arrangement. As indicated by the unconformities, the deposition of each series was succeeded by emergence of the region accompanied by erosion, and this in turn followed by submergence accompanied by deposition of the next series. Such repeated changes of relative level between land and sea, as here recorded for Proterozoic time

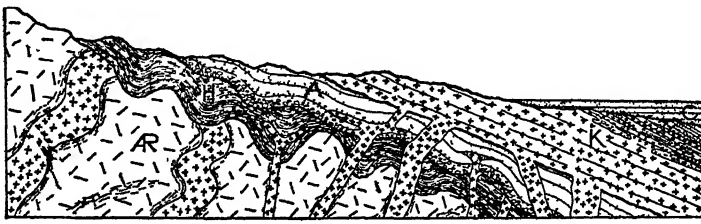


Fig 26

Diagram showing the principal subdivisions of the Proterozoic and their relation to the Archeozoic in the Lake Superior district *AR*, Archean; *H*, Huronian; *A*, Animikian; *K*, Keweenawan (From Chamberlin and Salisbury's "Geology," permission of Henry Holt and Company)

are among the most common and important phenomena of geologic history.

The Huronian rocks are principally quartzites, slates, schists, limestone (usually dolomitic), and some conglomerates and beds of iron ore, all of which are metamorphosed sediments. Locally some of these beds have not been metamorphosed. Considerable masses of igneous rock, some intrusive and some lava flows, also are included among the Huronian rocks. The Lower and Middle Huronian are usually much more metamorphosed and folded than the Upper, the latter being at times scarcely at all deformed or metamorphosed. Estimates show the aggregate (maximum) thickness of the Huronian rocks to be no less than two or three miles.

The Keweenawan, or latest Proterozoic series, is characterized by a great preponderance of lava beds which constitute the lower portion of the series; are prominent in its middle portion; and are

practically absent from the upper portion. Some idea of the stupendous and continuous volcanic activity of Keweenawan time may be gained from the fact that lava sheets, mostly not over a hundred feet thick each, accumulated to a depth of at least five or six miles. Between some of the later lava sheets, thin beds of sediment were deposited, while the upper part of the Keweenawan consists altogether of sediments, chiefly conglomerates and sandstones. The sediments are estimated to have a thickness of about three miles, so that the whole Keweenawan series must be some eight or ten miles thick.

Large bodies of granite intruded the Keweenawan and older rocks in various parts of the Great Lakes region prior to the opening of the Paleozoic era. This has been called the Killarney granite.

Lake Huron Region. — On the north side of Lake Huron according to Collins,[1] Huronian strata, 12,000 to 30,000 feet thick, are separated by an unconformity into a lower (Bruce) series and an upper (Cobalt) series. Both series are moderately metamorphosed and consist of quartzites, conglomerates, and limestones. The Huronian here rests upon profoundly eroded Archeozoic granite and is overlain, or cut by, the Keweenawan igneous series. Considerable bodies of late Proterozoic (Killarney) granite intrude all the formations just mentioned.

Rocky Mountain Region. — Perhaps the largest known area of Proterozoic rocks in North America is that in the Rocky Mountains of the northern United States and southern British Columbia. These rocks generally rest upon eroded Archean and they are overlain unconformably by Cambrian or still younger strata. This unconformity may more precisely be called a disconformity because the Cambrian and underlying eroded Proterozoic strata usually have parallel or nearly parallel stratification surfaces. The rocks consist mostly of quartzites, sandstones, shales, and limestones, associated with remarkably little igneous rock. Their thickness is usually two to five miles. Some of the strata (in Montana) contain fossils. In central Montana at least the Proterozoic strata appear to have been upturned, folded, and somewhat eroded before the deposition of the Cambrian. At present no satisfactory widespread subdivision of these rocks has been determined.

[1] W. H. Collins: *Geol. Surv. Canada*, Mem 143, 1925, p. 16.

Fig. 27

Proterozoic limestone in Goathaunt Mountain, Glacier National Park. The cliff is 1200 feet high. (After B. Willis, U S Geological Survey)

In Glacier National Park a great series of practically unaltered Proterozoic strata at least two miles thick forms a vast block which has been thrust-faulted over Mesozoic strata. In the Rocky Mountains 150 miles south of Glacier Park, a number of Proterozoic sedimentary formations, grouped under the term "Belt series," reach a total thickness of over 20,000 feet. The lower portion of this series has been largely metamorphosed into schist and quartzite, while the upper portion is mainly unaltered shale, sandstone, and limestone.

Grand Canyon of the Colorado. — In the Grand Canyon of the Colorado River, there are excellent exposures of Proterozoic rocks with their relations to the Archeozoic and Paleozoic well exhibited (Fig. 29). The Archean rocks, comprising granites, schists, and gneisses, were profoundly eroded before the immediately overlying Proterozoic rocks were deposited. These Proterozoic rocks, resting unconformably upon the Archean in the depths of the canyon, consist of two important formations. The lower one, nearly 7000 feet thick, is mostly sandstone and shale with some sheets of lava. The upper formation, separated from the lower by a slight unconformity, is over 5000 feet thick, and it is made up of shales, sandstones, and limestones. Both formations are tilted, and they are separated from the overlying Cambrian strata by an unconformity.

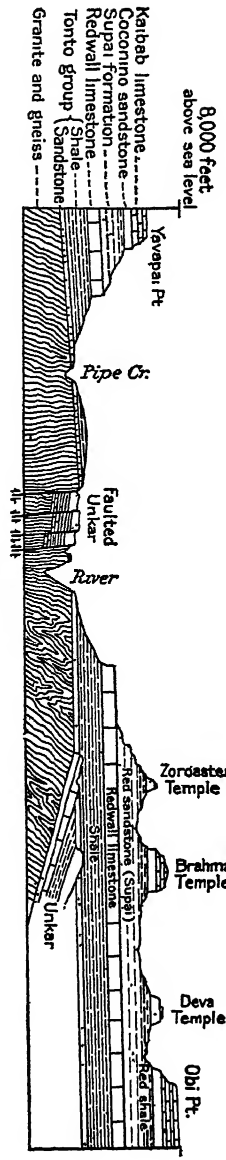


Fig. 28

Structure section across the Grand Canyon of Arizona, looking west from Yavapai Point to Obi Point. Unkar is Proterozoic and Tonto to Kaibab are Paleozoic. (After N. H. Darton, U S. Geological Survey.)

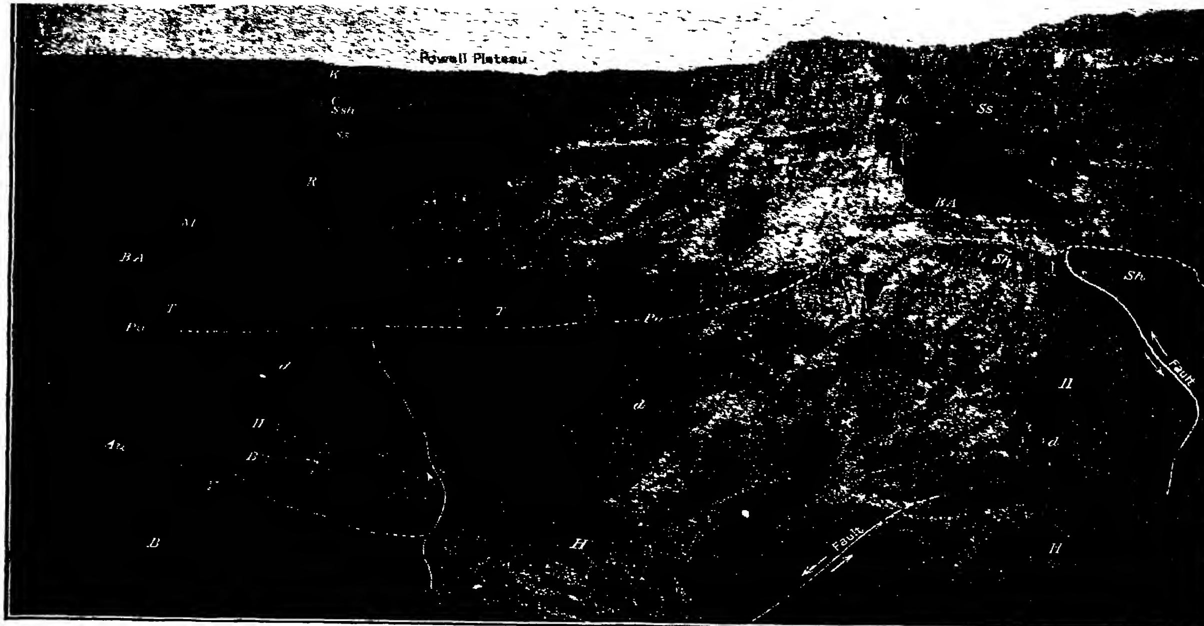


Fig 29

A view in the Grand Canyon of Arizona (Shinumo quadrangle) exhibiting the relations of Archeozoic, Proterozoic and Paleozoic rocks to each other. *V*, Archeozoic metamorphosed; *B*, *H*, *d* and *Sh*, Proterozoic partly metamorphosed strata with intrusive lava, *d*, *T*, *BA* and *M*, Cambrian strata; *R*, Mississippian; and *Ss*, *Ssh*, *C* and *K*, later Paleozoic. *Au*, Unconformity between Archeozoic and Proterozoic; *Pu*, unconformity between Proterozoic and Paleozoic. A vertical mile of strata is in view. Photo by Carkhuff. (After Noble, *U. S. Geological Survey Bulletin 549*.)

California. — In the White Mountains of middle-eastern California, there is a series of several stratified, somewhat metamorphosed formations consisting of dolomitic limestone, quartzite, sandstone, and slate, several thousand feet thick. These formations are considerably folded, and they lie unconformably below Lower Cambrian strata.

Correlation of Proterozoic Rocks. — The statements made regarding the difficulties of correlating the Archean rocks apply almost equally well here. Because Proterozoic rocks are more largely and distinctly sedimentary, and usually not so severely metamorphosed; usually separated into series by well-defined unconformities; and have fossils gradually coming to light in certain of the uppermost series, they afford a little more satisfactory basis for applying ordinary stratigraphic methods of correlation than do the Archean rocks. Remarkable similarities such as exist between the Lake Superior and Grand Canyon Proterozoic series are highly suggestive of correlation, though far from actually demonstrable at present. Lithologic and structural similarities alone are not safe methods of correlation. Future studies, however, are quite likely to yield satisfactory results in some cases at least.

Not only the general lack of fossils, but also the vast length of time of the Proterozoic era, are great difficulties in the way of correlation. Considering the time necessary for the deposition of the tremendous thickness of Proterozoic rocks, and the several long unrecorded time intervals, it seems reasonable to believe that the Proterozoic era was fully as long as the Paleozoic. Hence two similar series of Proterozoic rocks resting directly upon the eroded surface of the Archean in widely separated regions may in reality be far different in age because the Archean in one region may have remained unsubmerged very much longer than in the other. Or again, a Proterozoic series of one district may actually have been deposited during a time represented by an unconformity in another district.

Close of the Proterozoic (Killarney Revolution). — The Proterozoic era seems to have closed with North America all land, wider than at the present time, but not nearly so high on the average.

Canadian geologists have recently presented evidence to show that a mountain range at least 700 miles long, with a nearly east-west trend, was formed from Minnesota through northern

Wisconsin and Michigan to southwestern Quebec. Late Proterozoic and older rocks were there folded, uplifted, and intruded with granite before Cambrian strata were laid down upon the eroded edges of the Proterozoic. This range, called the Killarney Mountains, is probably the oldest known definitely located mountain range on the continent.

It is quite certain that there were late Proterozoic upturnings and uplift of strata elsewhere, as in the Grand Canyon region of Arizona, but as yet we have no accurate data in regard to the dimensions and trend of the resulting mountains.

Distribution of the Proterozoic. — As already stated, perhaps the largest Proterozoic area in North America is that of the Rocky Mountains in the northern United States and southern British Columbia. The well-known Lake Superior district of Proterozoic is also of large extent. There are considerable areas in eastern Canada west of Hudson Bay, and smaller areas in Newfoundland,

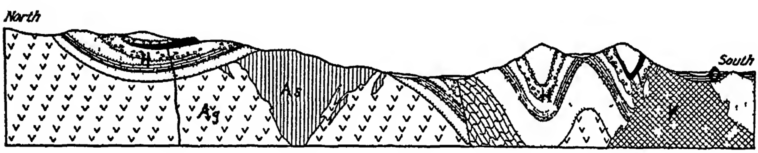


Fig 30

North-south structure section 45 miles long on the north side of Lake Huron Vertical scale greatly exaggerated *As* = Archeozoic schist; *Ag* = Archeozoic granite; *H* = Huronian strata (Bruce and Cobalt series, separated by unconformity) resting by unconformity upon Archeozoic rocks, black bands = Keweenawan basic intrusive igneous rocks; *K* = late Proterozoic (Killarney) granite; and *O* = Ordovician marine strata.

The principal events recorded in this section are as follows: Archeozoic schist intruded by much Archeozoic (Laurentian) granite; profound interval of erosion; deposition of Bruce strata, erosional interval, and deposition of Cobalt series; intrusion of basic igneous rocks into the Cobalt strata; intense folding in late Proterozoic time, still later intrusion of the Keweenawan (Killarney) granite; long interval of erosion; and deposition of Ordovician strata in the sea. (Section modified after W H Collins, Geological Survey of Canada.)

Nova Scotia, the Piedmont Plateau, at several places in the Mississippi Basin, Texas, Arizona (especially in the Grand Canyon), Nevada, eastern California, and at various places in the Rocky Mountain system throughout the United States and Canada.

Foreign Proterozoic. — Proterozoic rocks are thought to exist in all continents. In the Highlands of Scotland, the Torridon sandstones and shales, about 10,000 feet thick, are quite certainly of Proterozoic age, since they lie unconformably between the Archean complex below and well-defined Cambrian above.

The large pre-Cambrian rock area in Scandinavia, which in many respects is similar to that of Scotland, also contains considerable bodies of sediments (at least 10,000 feet thick) of Proterozoic age. As in the Lake Superior region, iron ore occurs in some of the Swedish Proterozoic.

In Finland, France, Germany, Spain, and probably in India and Brazil, Proterozoic rocks are known.

It should be noted that in several of the foreign countries there appears to be a division of the Proterozoic group into at least two series separated by unconformities.

Life and Climate of the Proterozoic Era. — As has been mentioned, determinable fossils have been found in the upper Proterozoic rocks of Montana and the Grand Canyon of the Colorado. These fossils include Algæ, Bacteria, Worm tracks, Sponges, and fragments of Crustaceans. In Europe a few similar fossils have been found. Recently the discovery of Radiolarians in the Proterozoic rocks of France has been reported. "The traces of pre-Cambrian (animal) life, though very meager, are sufficient to indicate that the development of life was well advanced long before Cambrian time began. . . . Stratigraphically, this fragment of what must have been a large fauna occurs over 9,000 feet beneath an unconformity at the base of the upper portion of the Lower Cambrian in northern Montana." [1] More and still older forms are quite likely to be discovered, though the remains thus far found are those of very thin-shelled animals and hence not so favorable for fossilization. Most animals of the time were probably without shells or other hard parts.

Very recently Walcott has described a number of species of calcareous Algæ from the Belt series (Proterozoic) of Montana and one (discovered by Lawson) from a Huronian limestone of western Ontario, these being the oldest known well preserved fossils. These Algæ were very simple plants (Thallophytes) which lived in water. They were hemispherical or cylindrical bodies which secreted crudely concentric layers of carbonate of lime

[1] C. D Walcott: *Jour. Geol.*, Vol 17, 1909, p. 196.

from 1 to 15 inches in diameter They occur in distinct beds through hundreds or even thousands of feet of Proterozoic limestones. Walcott has also described what seem to be fossil Bacteria, which are single-celled, tiny plants, from the late Proterozoic rocks.

Graphite and carbonaceous material so often disseminated through the shales and schists almost certainly indicate the existence of life. Likewise beds of limestone (even near the base of the Proterozoic) and iron ore are rarely ever known to have been formed except through the agency of organisms.

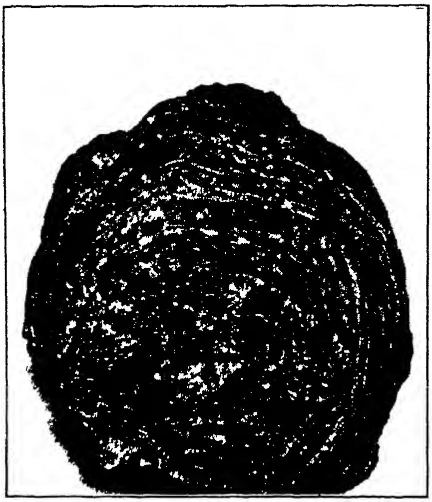


Fig 31

A Proterozoic Alga from Glacier National Park, Montana. Diameter, 4 inches. (Photo by the author.)

Since the great masses of Proterozoic sediments are of quite the usual sort like those formed in later eras, and since life surely existed, we can be certain that the climate of the time was favorable for the operations of ordinary geologic processes and hence not fundamentally different from that of comparatively recent geologic time.

According to a discovery made a few years ago, there is positive evidence for considerable glaciation in Canada during early Proterozoic time. Conglomerate beds at the base of the Huronian are regarded as of glacial origin since there are "angular and subangular boulders of all sizes up to cubic yards, enclosed in an unstratified matrix. These boulders are often miles from any possible source. Recently, striated stones have been broken out of their matrix in the Lower Huronian of the Cobalt-Silver region, giving still stronger proofs that the formation is ancient boulder clay."[1]

[1] A. P. Coleman: *Jour. Geol.*, Vol. 16, p. 149.

This glacial deposit has been found at various places within an area of thousands of square miles north of Lake Huron. A climatic condition favorable for glaciation so early in the earth's history is, to say the least, distinctly opposed to ideas of climate of such early geologic time based upon the Laplacian hypothesis of earth origin.

Economic Products. — The greatest iron mining region in the world is the Lake Superior district in Minnesota, Michigan, and Wisconsin. Some of these iron ores are in the Archean, and some in the older Huronian rocks, but the principal deposits are in the Upper Huronian. These iron ores occur as thick beds in the sedimentary series. Often the iron ore deposits have been enriched by the work of underground waters. The Lake Superior district produces many millions of tons of iron ore, or far more than the production of any foreign country.

The greatest deposits of native copper in the world are in the Keweenawan series on Keweenaw Point, Michigan. Copper has been found in small quantities in the lava beds, and underground waters have dissolved out this copper and deposited it in more concentrated form in fissures and openings of the rock, and also in porous conglomerates. Immense quantities of native copper have been mined here during the past fifty years.

PALEOZOIC ERA

CHAPTER VI

THE CAMBRIAN PERIOD

THE Cambrian represents the earliest period of the great Paleozoic era, and the rocks which make up the Cambrian system include the oldest known of the normal fossiliferous strata. Since these strata are the oldest which carry abundant organic remains, it follows that they are the earliest formed rocks to which the ordinary methods of subdividing and correlating rock masses can be applied. From the Cambrian on, the legible records of events of earth history are far more abundant and less defaced than those of pre-Cambrian time. From now on we shall be able to trace the changing outlines of the relief features of the continents and the evolution of organisms with some degree of definiteness and satisfaction, though a vast amount of work yet remains to be done both as regards discovery of new records and the interpretation of records old and new.

ORIGIN OF NAME, SUBDIVISIONS, ETC.

The oldest Paleozoic rocks were first carefully studied independently in the British Isles by the two able geologists, Sedgwick and Murchison, before the middle of the nineteenth century. Murchison applied the name "Silurian" to the great series of oldest fossiliferous strata and divided them into Lower and Upper Silurian. Sedgwick, however, considered that the very oldest fossil-bearing rocks should be separately designated, hence his application of the term "Cambrian," from Cambria an old Latin name for a part of Wales. The Cambrian is now recognized the world over as the oldest Paleozoic system.

In North America a threefold subdivision of the Cambrian system is recognized as follows:

	General	New York-New England
Upper Cambrian	Ozarkian Croixian	Little Falls Potsdam
Middle Cambrian	Acadian	Acadian
Lower Cambrian	Waucobian	Taconian

In the typical regions these strata are superposed one above the other in regular order without unconformity, but careful study has shown that, passing upward in the system of strata, there is a gradual change in the character of the fossils, particularly the Trilobites which are so common and widespread in the rocks. Thus the Lower Cambrian strata are generally characterized by the Trilobite genus Olenellus, with its various species, and this characteristic assemblage of Trilobites is called the Olenellus fauna. This does not mean that Olenellus invariably occurs in Lower Cambrian strata, or that other genera of Trilobites and other fossils may not be present. In a similar way the Paradoxides and the Dikellocephalus faunas are the chief characteristics of the Middle and Upper Cambrian respectively. Such stages or life zones in the geologic column are commonly referred to as horizons. It should be made clear that the genus Olenellus became extinct before the Middle Cambrian strata were deposited; the Paradoxides disappeared before the Upper Cambrian was deposited; and the Dikellocephalus before the deposition of the succeeding Ordovician strata, though it is not meant that sharp lines separate these faunas. Thus each of the faunas becomes an important geologic time or horizon marker. A representative of each of these genera of Trilobites is shown in Fig. 47.

These principles, here laid down as a basis for the subdivision of the Cambrian system, apply equally well to the succeeding rock systems, though many organisms other than Trilobites are used for the purpose.

Distribution and Character of the Rocks

General Distribution. — On the accompanying map (Fig. 32) the surface distribution of Cambrian rocks is shown, that is to say the locations of the areas in which Cambrian strata are known to outcrop. The principal areas are seen to be in Newfoundland, New York, through the Appalachian range, south of Lake Superior,

southeastern Missouri, Oklahoma, central Texas, Nevada, eastern California, and at various places in the Rocky Mountain region.[1]

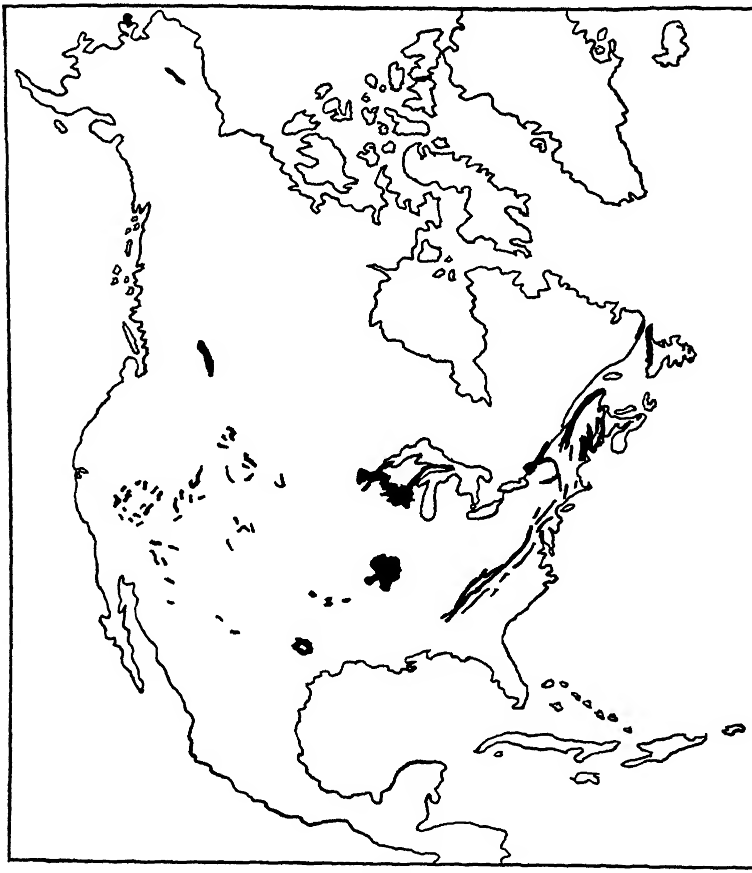


Fig 32

Map showing the surface distribution (areas of outcrops) of Cambrian, and some very closely associated Lower Ordovician, strata in North America (Modified by W. J. M after Willis, U S Geological Survey)

[1] Readers who are not very familiar with the geography and physiography of the United States should, whenever necessary, refer to the map at the end of Chapter XIX Good atlas maps of North America and of the United States should also be at hand.

Because Cambrian rocks have so often been removed by erosion, or have been so largely covered by later sediments, or highly folded so that outcropping edges only are now exposed, the surface distribution as indicated on the map fails to give any adequate idea of the former or even present real extent of strata of this age. Thus Cambrian strata are definitely known to have been almost completely removed from several thousand square miles of the northern New York region, and Cambrian rocks have certainly been similarly removed from many other regions. Again, the distribution of the outcrops, together with many deep well sections (Fig. 33), make it certain that Cambrian strata concealed under nearly horizontal later strata spread across much, if not all, of the Mississippi Valley from the Rockies to the Appalachians, while in the Appalachian Mountains Cambrian rocks are really much more extensive than the mere outcropping edges of the upturned strata. There is no reason, however, to think that the vast area of pre-Cambrian rock around Hudson Bay, the Atlantic Coast from New Jersey southward, and the Pacific Coast region from northern California northward through Alaska, were ever covered by the Cambrian sea.

The difference in the distribution of the Lower and Upper Cambrian strata is a prime consideration. Thus the Lower Cambrian is entirely absent from the whole Mississippi Valley. Otherwise the same general areas are occupied by both Lower and Upper Cambrian strata.

Character of the Rocks. — Cambrian rocks consist very largely of shallow water sediments such as conglomerates, sandstones (Fig. 35), and shales, with well-preserved ripple marks very common. Deeper or clearer water deposits such as limestone, are, however, important in the Appalachians, Vermont, Nevada, the Rocky Mountain region, and British Columbia. When these sediments were deposited in the Cambrian sea they were like ordinary gravels, sands, marls, and limy oozes now forming in the ocean, especially over the continental shelf areas and their borders. Since their deposition they have been changed into the corresponding harder rocks such as conglomerates, sandstone, shales, and limestones, or, in some cases as in New England, metamorphosed into quartzites, schists or slates, and crystalline limestones (marbles). In many regions the Cambrian strata have been highly folded and faulted.

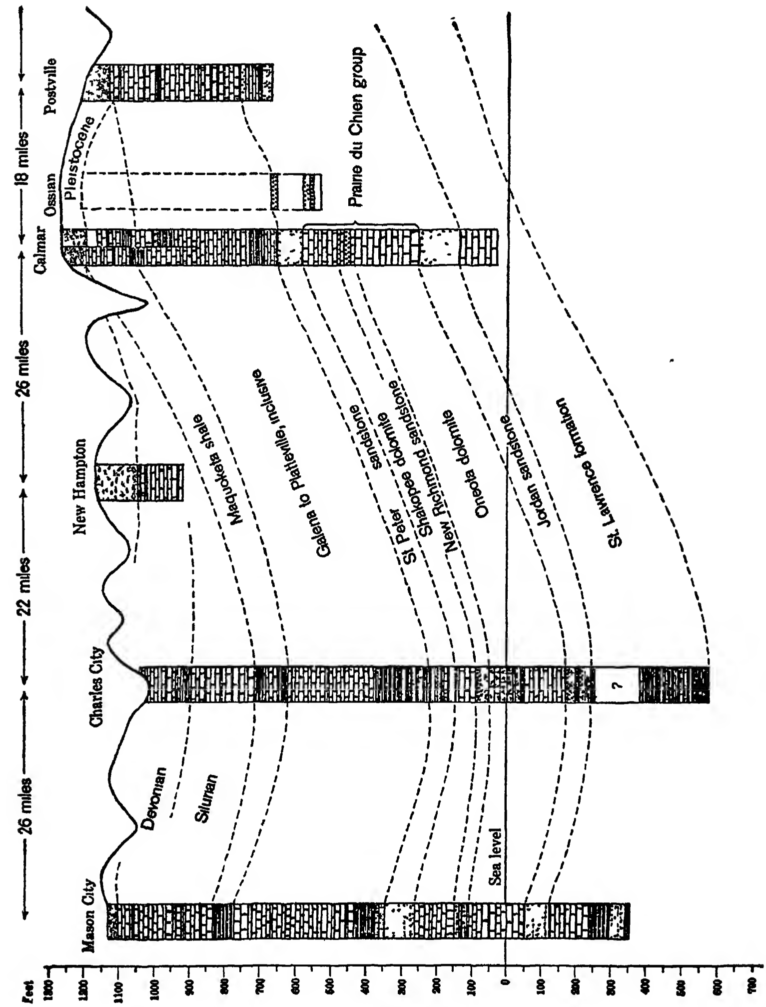


Fig 33

Geologic section through northeastern Iowa, showing how character, thickness, and distribution of deeply buried rock formations can be determined by a comparison of well records. St Lawrence and Jordan formations are Cambrian; Oneota to Maquoketa inclusive are Ordovician; and above these are Silurian and Devonian strata as indicated. (After W. H. Norton, U. S. Geological Survey.)

The following statements will give a fair idea of the subdivisions, character, and thickness of the Cambrian system in widely separated parts of the United States. In eastern California (Inyo Mountains) the Cambrian is well represented, consisting of Lower Cambrian sandstone, shale, and limestone 10,000 feet thick overlain by 1000 feet of Middle Cambrian sandstone and limestone, and this in turn by about 1000 feet of Upper Cambrian limestone and shale, making a total thickness of 12,000 feet of Cambrian. At least as great a maximum thickness occurs in the Rocky Mountains of the northern United States where the Middle and Upper Cambrian strata (mostly limestone) are much thicker than they are in California.

In the southern Appalachian region Lower Cambrian sandstone and conglomerate reach a thickness of fully 10,000 feet; Middle Cambrian limestone and shale, 4000 feet; and Upper Cambrian limestone and sandstone, 8000 feet — a total of 22,000 feet of Cambrian.

Upper Cambrian rocks occur widely in the Mississippi Valley. These are largely sandstones of widespread extent, and they are generally less than 1000 feet thick.

Thickness of the Cambrian and Igneous Rocks. — The thickness of Cambrian strata in North America varies from less than 1000 feet to a maximum of over 20,000 feet. In addition to the thicknesses above given, mention may be made of a thickness of 8000 to 12,000 feet in Virginia and Pennsylvania, and of 9000 feet in Utah. North American Cambrian is singularly free from igneous rocks and thus presents a remarkable contrast with the preceding eras.

Physical History

Great Basal Unconformity. — We have already learned that a profound and seemingly almost universal unconformity separates the Archeozoic and Proterozoic rocks. Another great unconformity separates the Proterozoic and Paleozoic rocks. Cambrian strata rarely if ever fail to rest upon the eroded surfaces of either the Archeozoic or the Proterozoic. C. D. Walcott stated in 1914 that no definitely proved transition rocks between the Cambrian and pre-Cambrian are known in North America. It has been definitely proved, as for example in the Adirondack region, to be quite the rule that the Cambrian sediments not only rest upon

an eroded surface of older rocks, but that the surface of these latter had been worn down to the condition of a more or less well-developed peneplain. Accordingly, just before and during early Cambrian time, most, if not all, of North America must have been dry land suffering erosion. Conglomerates containing pebbles of the older rocks are of very common occurrence at the base of the

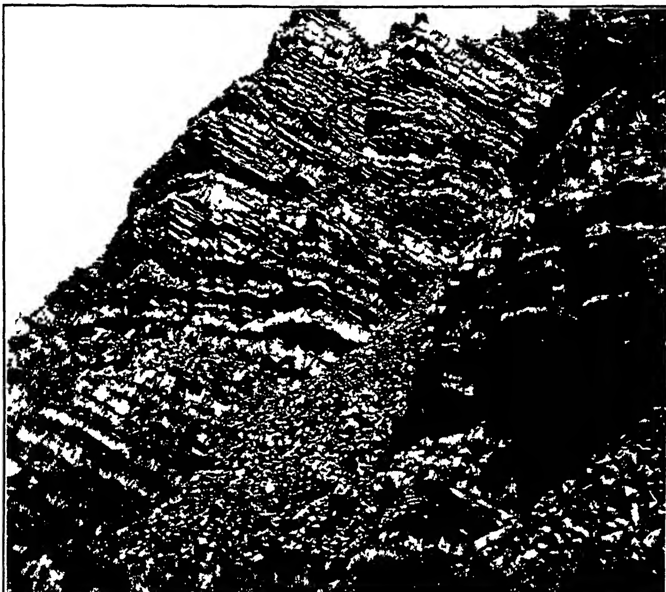


Fig 34

Lower Cambrian strata at Deep Spring Valley, California (Photo by the author.)

Cambrian sediments. The great duration of this erosion interval which produced such a profound unconformity, not only in North America but in other continents as well, is regarded as one of the greatest physical events of its kind in the history of the earth since the beginning of Paleozoic, or rather late Proterozoic, time.

Early and Middle Cambrian. — During Early (Lower) Cambrian time partial submergence of North America resulted in the development of two long narrow arms of the sea, one in the east and

Fig. 35

Upper Cambrian (Potsdam) sandstone in the Ausable Chasm of northeastern New York. The rock is distinctly stratified and full of ripple-marks (Courtesy of the New York State Museum.)

the other in the west, as shown on the accompanying map Fig. 36. These marked the beginning of the Appalachian and Cordilleran geosynclines, respectively, which were more or less persistent during Early and Middle Paleozoic time (see Fig. 138). As we have already learned, such a submergence may have been produced either by rising sea level or subsidence of the land, or both. In the

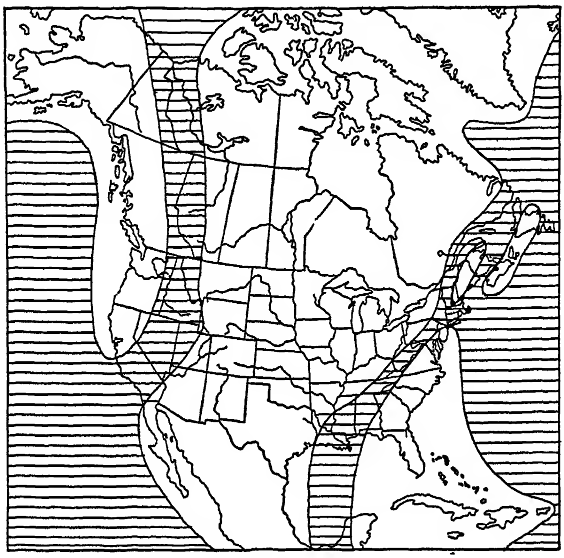


Fig 36

Paleogeographic map of North America during Lower (Early) Cambrian time. White areas, land; ruled areas, sea (Principal data, modified by the author, from maps by B Willis and C. Schuchert)

case of the Cambrian submergence there appears to be no escape from the conclusion that a rise of the sea was an important factor, since the development of such an extensive peneplain surface implies that the continent must have remained almost unaffected by diastrophic movements for a long time, and the tremendous volume of material removed and dumped into the sea must have very appreciably raised its level.

Wherever Lower Cambrian marine strata (actually exposed or

concealed) rest directly upon pre-Cambrian rocks we can be sure that such areas were submerged under the early Cambrian sea, because Lower Cambrian strata could have formed only during that time. To these areas must be added still others from which the rocks have been removed by erosion. Further, since the later Cambrian strata almost invariably rest in perfect conformity upon the earlier, we can be sure that any region occupied by later, but not earlier, Cambrian rocks was never covered by the earlier Cambrian sea because the conformity proves that there was no erosion interval during which any of the earlier Cambrian strata were removed before the deposition of the later. Again, many large areas were almost certainly dry land during early Cambrian time because there is not the slightest evidence of any sort that deposition went on over those areas during that time. The principles here set forth are of fundamental importance in constructing a paleogeographic map of North America for early Cambrian time, and the same principles must be kept in mind in considering the paleogeography of any given region during succeeding time.

A general withdrawal of the eastern arm of the sea marked the close of Lower Cambrian time, but the western sea (or mediterranean) remained. This was the condition of the continent during Middle Cambrian time, with the exception that eastern New England and parts of New Brunswick and Nova Scotia were submerged.

Late Cambrian. — During Upper Cambrian time more and more of the continent tended to become submerged until the geographic conditions were much as depicted upon the next paleogeographic map (Fig. 37). The sea transgressed northward over the great interior land to about the northern border of the United States, forming a vast interior sea. Fully one-third of the continent was flooded. As the map shows, there were four large land areas — Appalachia, Canadia, Cascadia, and Mexicoia.[1] These four land areas, with somewhat changing borders, were remarkably persistent during the repeated Early and Middle Paleozoic flooding of the continent (see Fig. 138).

The northward trangression of this great interior sea in the eastern United States is clearly established by the fact that studies of actual outcrops and deep well sections show successively younger

[1] The term "Mexicoia" is here proposed as a designation for the persistent Paleozoic land mass in the Mexican area.

and younger Cambrian sediments deposited by overlap northward upon the pre-Cambrian rock surface. We also know that this interior sea was shallow because of the character of the sediments which are very largely clastic such as sandstones and shales often ripple marked, and with conglomerates at the base. Some heavy limestone beds like those in eastern New York, and between Virginia and Missouri, tell of clearer, possibly deeper, water in those places.

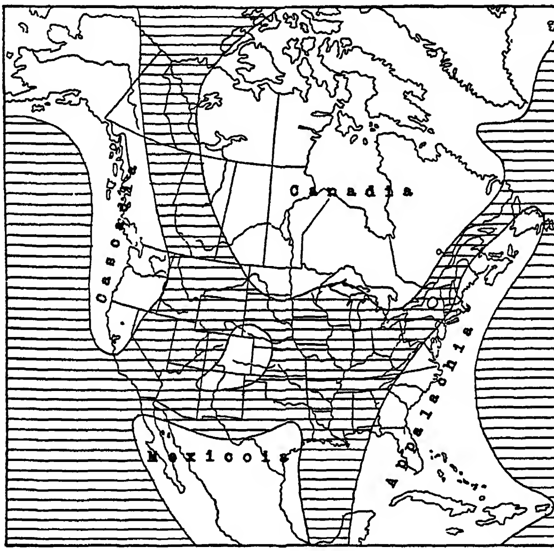


Fig. 37

Paleogeographic map of North America during middle Upper Cambrian time White areas, land; ruled areas, sea (Principal data, modified by the author, from maps by B Willis and C Schuchert)

Late in the Upper Cambrian there seems to have been a withdrawal of the sea from the western one-half of the continent, leaving the eastern side about as it was in the Middle Cambrian.

Duration of the Cambrian. — The physical events above outlined prove that the Cambrian period represents a long time, the best estimates ranging from 3,000,000 to 5,000,000 years, though it should be emphasized that we have no exact standard of compari-

son in years. The only object in presenting such figures is to impress upon the student the fact of the vast length of time involved. Though the succeeding periods were by no means equal in duration, minimum estimates would make no one of them less than 3,000,000 years long. Estimates based upon the principle of radioactivity involve much greater time for a Paleozoic period.

Close of the Cambrian. — Throughout Cambrian time, and even at its close, North America was not affected by any really great physical disturbances such as mountain-making or vulcanism, though recent studies seem to show that a belt extending from Vermont to northern New Brunswick was considerably elevated, probably without much folding, at the close of the period.

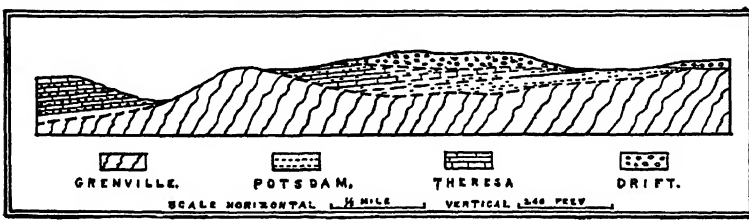


Fig 38

Structure section in Saratoga County, New York, showing how Upper Cambrian strata overlap upon a hillock of pre-Cambrian rock (Grenville). (After W. J Miller, *N. Y. State Mus Bul. 153*)

According to Schuchert the Cambrian period closed with "a very wide and probably complete retreat of the epeiric (continental) seas from the interior parts of North America, leaving the continent all or nearly all dry land."

Foreign Cambrian

Europe. — Like that of North America, the Cambrian rocks of Europe generally rest upon the profoundly eroded surface of either Proterozoic or Archean rocks. The physical geography of the continent, however, differed considerably because the distribution of the rocks shows that the Early Cambrian sea was almost wholly limited to northern Europe, while the Middle Cambrian sea transgressed farthest over much of France, Germany, Bohemia, Spain, and Sardinia, and in the Late Cambrian the sea spread widely over Europe, as shown on the accompanying map (Fig. 39).

In Wales and Brittany the Cambrian strata appear to have a maximum thickness variously estimated at from 12,000 to 20,000 feet, while in southern Sweden the whole Cambrian is only about 400 feet thick. Like those of North America, the rocks are mainly clastic sediments of shallow water origin such as conglomerates, sandstones, and shales. In western Europe, for example in Wales

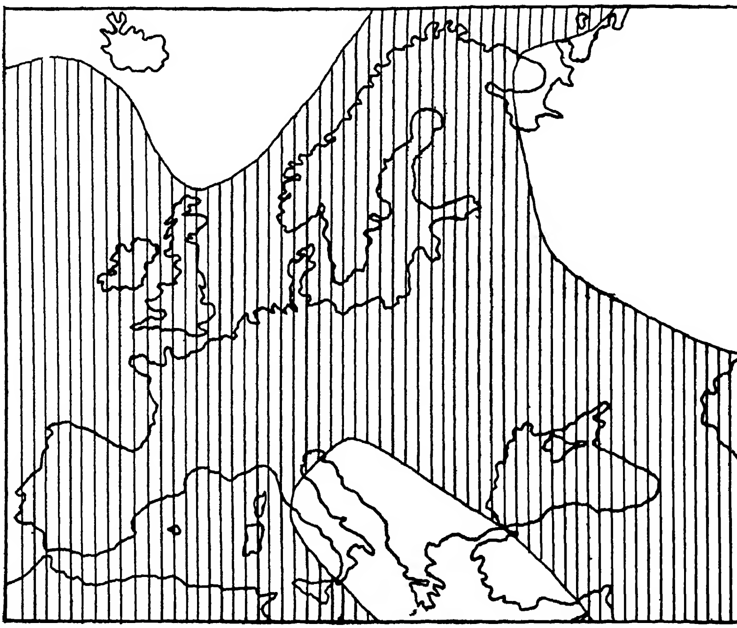


Fig 39

Paleogeographic map of Europe during Upper Cambrian time. White areas, land; ruled areas, sea (Modified by the author after F. X Schaffer)

and southern Scandinavia, the Cambrian strata are thoroughly indurated and usually highly folded, but in eastern and central Europe, for example in Russia, most of the strata are practically horizontal, and even unconsolidated beds of sand and clay have been found. Unconsolidated beds of so great age are truly remarkable.

The Cambrian period closed in Europe without any important physical disturbance.

Other Continents. — The Cambrian of other continents has generally not been well studied, but rocks of this age are known in Australia, Tasmania, India, China, Korea, Siberia, and Argentina. Only slightly folded or tilted strata of Cambrian age up to 20,000 feet thick are known in northern China. Glacial deposits in China, Norway, and Australia will be described under the next heading.

Climate

Very distinct evidences of glaciation are known in the earliest Cambrian or possibly late Proterozoic of China, Norway, Australia, and perhaps also South Africa. At the base of the thick section of Cambrian strata in China "on the Yangtse River, 31° Lat., i.e. as far south as New Orleans, not high above sea level, a large body of glacial material (170 feet thick) was discovered. . . . It demonstrates the existence of glacial conditions in a very low latitude in the early Paleozoic." [1]

At Lat. 70° N. in Norway, glacial deposits containing clearly striated pebbles have been found resting upon a distinctly smoothed and striated surface of hard rock.

In southern Australia glacial beds of similar age and considerable thickness are distinctly folded along with the enclosing strata.

The significance of these earliest Paleozoic glacial deposits is difficult to exaggerate in considering the climate of the time. The old idea, based upon the Laplacian Nebular hypothesis, that early Paleozoic climate was notably warmer, moister, and richer in carbon dioxide than now, is directly refuted by the evidence of glaciation. Such evidences of glaciation, combined with the character and distribution of the organisms, indicate that Cambrian climate was not essentially different from that of comparatively recent geologic time, but that climatic conditions were much more uniform over the earth than now.

Economic Products

Cambrian rocks, such as the Potsdam sandstone and Little Falls dolomite in New York, furnish considerable quantities of building stone for local use.

Roofing and other slates of Cambrian age are extensively quar-

[1] B Willis: *Researches in China* (Vol. 2), published by Carnegie Institution of Washington.

ried in Vermont and eastern New York. Also the famous slate quarries of Wales are in rocks of this age.

No very important metalliferous deposits are known in Cambrian rocks

LIFE OF THE CAMBRIAN[1]

Stage of Evolution of Cambrian Life. — The life of the Cambrian possesses a particular importance because, excepting the few scant organic remains found in upper Proterozoic rocks, the rocks of this age contain the oldest known assemblage of distinct fossils. Many hundreds of Cambrian species have been described. Even here, however, the organic record is very incomplete both because many Cambrian fossils have not yet been discovered and because a vast number of Cambrian organisms must never have been preserved as fossils. Although Cambrian fossils are scant as compared with those of other Paleozoic systems, nevertheless a striking fact is the large number and complexity of organisms represented. All of the sub-kingdoms of invertebrate animals are represented, though nearly always by only the simpler types of each sub-kingdom, and this together with the positive evidences for pre-Cambrian life, makes it perfectly evident that organisms existed and developed (evolved) for a vast length of time before the opening of the Cambrian. It is generally agreed that fully half of the evolution of animals had taken place before the beginning of the Cambrian period, but that plants had not developed beyond the single-celled stage.

In spite of so much pre-Cambrian evolution of animals, it is to be remembered that, as a result of post-Cambrian evolution, literally enormous advancement has been made, so that Cambrian forms are really simple or primitive as compared with many of the highest living forms. To illustrate, there is a vast gulf between the degree of organization of the highest Mammals of today and the highest forms (simple Arthropods) of Cambrian time, and all of this development has been gradually accomplished since Cambrian time.

Passing upward even within the Cambrian system, the fauna

[1] In the study of the life of each period from the Cambrian to the present the student should, if necessary, refer to the outline classifications of plants and animals in Chapter I.

shows a gradual progress toward more highly developed or organized forms.

Apparent Suddenness of Appearance of the Cambrian Forms. — The apparent suddenness of appearance of so many highly developed organisms even in the early Cambrian has caused much discussion by way of attempted explanation. Geologists are agreed that this seeming sudden appearance of so many forms is due to imperfection of the record either because of unfavorable conditions for the preservation of fossils in the pre-Cambrian sediments, or because fossils, though once present in those rocks, have been obliterated by subsequent changes or metamorphism. Further, it is agreed that the first organisms were plants because animal life is ultimately dependent upon vegetable matter as a food supply.

It should be recognized that the metamorphic, or crystalline, character of all Archean and most Proterozoic rocks is obviously unfavorable for preservation of determinable fossils. Thus, Archean sedimentary rocks have flakes of graphite (carbon) disseminated through them and, though such carbon is of organic origin, the original organic structures have been entirely obliterated so that crystallized carbon only remains after the intense metamorphism. Such an explanation, however, does not by any means answer the whole question, because, at a number of localities, thousands of feet of non-metamorphosed pre-Cambrian strata are known and, except in very few cases in the later of these rocks, distinct fossil forms of animals are not known.

Brooks [1] has advanced the hypothesis that the early living forms (plants and animals) were single celled, and that they originated and lived in the surface portions of the ocean. Because of the lack of severe struggle for existence in such environment, pelagic (free-swimming) plants have to this day remained largely primitive or single celled. For similar reasons the unicellular animals long failed to evolve higher forms because of easy existence in contact with much food and sunlight. Such forms were of gelatinous consistence and not favorable for preservation as fossils. Not until the attachment to the bottom or along shore were conditions favorable for the development of higher forms by the aggregation of cells. The plants first spread to the shore waters and thence over the land, so that gradually the shore waters became

[1] W. K. Brooks: *Jour. Geol*, Vol. 2, 1894.

clearer and richer in organic material and hence more suitable habitats for animals. The animals once established along shore, about the beginning of the Cambrian or late in the pre-Cambrian, are conceived to have made rapid progress in evolution because the struggle for existence became severe on account of greater crowding in this more restricted environment. Support became necessary as well as means of defense, therefore hard parts were developed, and such hard parts could be preserved as fossils. In harmony with this hypothesis is the important fact that pre-Cambrian and early Cambrian fossil shells are mostly very thin, heavy shells apparently not having been evolved till later.

Another hypothesis "assumes that the first forms of life were simple plants that originated in the land waters. . . . This hypothesis further assumes that the early animals, to a greater or less degree, had their origin in the same waters, and like the plants on which they were dependent spread thence to the sea and out upon the land. It is assumed that there might be considerable development of aquatic forms of animal life . . . in the land waters before they became denizens of the seas, and their appearance in the latter might be at some rather advanced stage of their evolution and hence be seemingly sudden." [1]

Plants. — There are certain rather obscure impressions and other more distinct cluster-like forms which may be sea-weeds, but their identification is not at all positive. As stated above, simple plants at least must have been abundant since animals ultimately depend upon plants for food. Their scarcity as fossils is doubtless due to the unfavorable character of the simple (soft) marine plants for fossilization.

Recently certain problematical Cambrian fossils, long known by the name "Cryptozoön," have been determined as Algæ by Walcott. They secreted concentric layers of carbonate of lime and lived in water. In some localities, as near Saratoga Springs, New York, distinct beds or "reefs" of such Algæ occur in limestone (see Fig. 40).

There is no evidence that any types of plants other than single-celled water-dwelling forms existed during Cambrian time. This is a remarkable fact not only in view of the tremendous lapse of Archeozoic and Proterozoic time, but also of the profound post-Cambrian evolution in the plant world.

[1] Chamberlin and Salisbury: *Geology*, Vol 2, p. 302.

Protozoans. — *Foraminifers* have been found even in Lower Cambrian rocks. These forms are very much like the modern marine forms, and it is an interesting and important fact that such very simple types have persisted throughout all of geologic time from the Cambrian to the present, while profound evolutionary changes were taking place in the animal kingdom. *Radiolarians* are not known as fossils. Many Protozoans doubtless existed, but

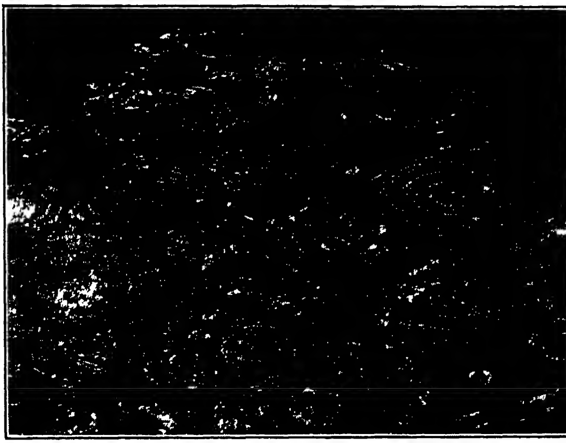


Fig 40

Calcareous Algæ, *Cryptozoön proliferum*, forming a reef in Upper Cambrian limestone near Saratoga Springs, New York. (After H P Cushing, *N. Y State Mus. Bul 169*)

very few secreted shells, and hence not many species could have been preserved as fossils.

Porifers. — True *Sponges* (Fig. 41) were fairly abundant throughout the period, their siliceous remains being especially common as fossils.

Cœlenterates. — *Hydrozoans* were represented by both the so-called "Jelly-fishes" and the Graptolites. Recognizable casts and impressions of Jelly-fishes (Fig. 42), which creatures consist wholly of soft parts, have been found, and these are remarkable freaks of fossil preservation. *Graptolites* (Fig. 59) were common, especially in the later Cambrian. These were slender, plume-like,

delicate forms consisting of colonies of cells. They were pelagic or free to float in the open sea. One genus of Graptolites, confined to a horizon near the summit of the Cambrian, is well-nigh

Fig. 41

A Cambrian Sponge, *Leptomitus zitteli* (After Walcott)

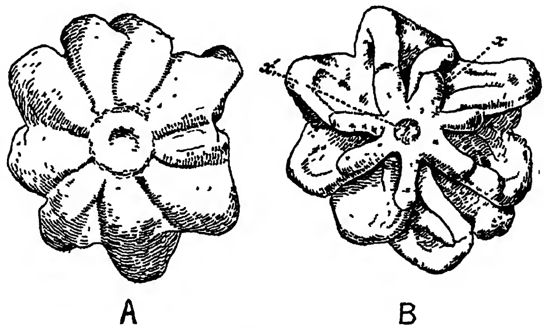


Fig 42

A Cambrian Jelly-fish, *Brooksella alternata* (After Walcott, from Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company)

world-wide in its distribution and beautifully illustrates the importance of such forms for purposes of correlation over wide areas. It should be stated that Graptolites occur only in the older Paleozoic strata.

Anthozoans (Corals) were more doubtfully present because the fossil forms so greatly resemble Sponges (Fig. 43), but recent study seems to indicate that some at least were true Corals. Locally such coral-like forms were common enough to form reefs It seems quite clear that the Corals evolved from Cambrian Sponges.

Fig. 43

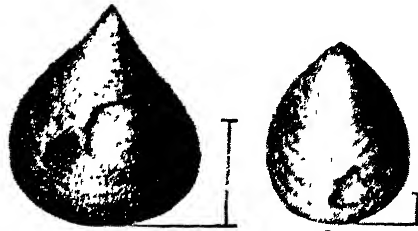
A Cambrian Sponge or Coral, *Archeocyathus rensselaericus* (After Walcott)

Echinoderms. — Of the stalked Echinoderms the very simplest class, called *Cystoids*, are known to have existed. There were the bladder-like forms, sometimes with rudimentary arms, set on segmented stems (Fig. 60a). *Holothuroids* ("sea cucumbers") have been found in the Cambrian of British Columbia.

These are of special interest because they represent highly organized forms of Echinoderms.

Worms.—Tracks and borings of marine Worms are common, but no actual remains are known.

Molluscoids.—*Brachiopods*, next after the Trilobites (simple Crustaceans), are the most important Cambrian fossils (Fig. 44). There are two important general groups of Brachiopods, namely, the Inarticulates, in which the horny shells or valves are not joined together by a hinge, and the Articulates, in which the heavier calcareous shells are joined together by a hinge structure. The former are simpler and lower in organization, and, from the standpoint of evolution, it is important to note that Cambrian (and probably pre-Cambrian) Brachiopods were mostly Inarticulates, the Articulates not becoming common till in the Upper Cambrian. In the post-Cambrian periods the Articulates greatly outnumbered the Inarticulates, and they are the most common of all fossil shells in the Paleozoic rocks. The Brachiopods stand out conspicuously as a remarkably persistent class of animals ranging from pre-Cambrian time to the present, and, although there have been very many species and genera



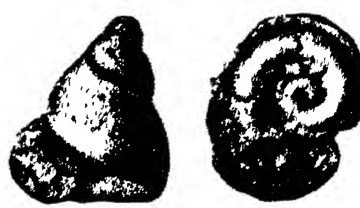
a b

Fig 44

Cambrian Brachiopods: *a*, *Lingulella prima*; *b*, *Lingulella acuminata*. (After Walcott)

Fig. 45

A Cambrian Pelecypod (*Fordilla troyensis*). Shell on right and cast on left, much enlarged (After Walcott.)



a Fig 46 b

Cambrian Gastropods: *a*, *Matherella saratogensis*, *b*, *Pelagiella minutissima*. (After Walcott.)

changes, the class as such has been very little changed. A few genera, but no species, have persisted from the Cambrian to the present. At least 7000 species of Brachiopods are known, most of them from the Paleozoic, but only about 200 species now exist. Many hundreds of species are known from the Paleozoic rocks alone, and by studying their gradual changes in species and genera, they have come to rank among the most valuable fossils as geologic time markers and for purposes of correlation.

Mollusks. — All the principal fossil-forming types of Mollusks were represented. *Pelecypod* shells are small and comparatively rare, being mostly found in the Lower Cambrian (Fig. 45). From

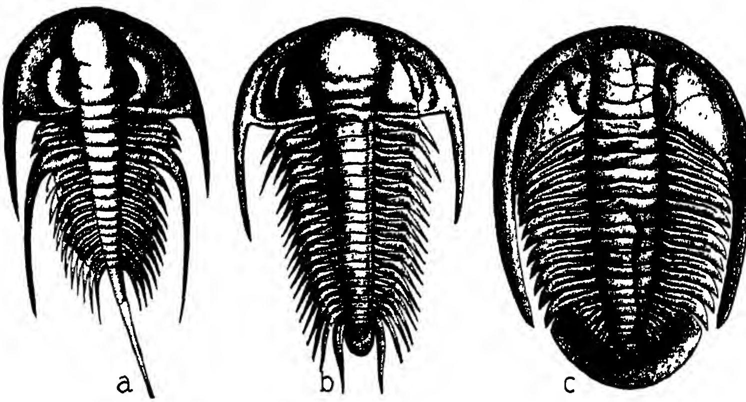


Fig 47

Cambrian Trilobites, restored forms: *a, Olenellus gilberti*, characteristic of the Lower Cambrian; *b, Paradoxides bohemicus*, characteristic of the Middle Cambrian; *c, Dikellocephalus pepinensis*, characteristic of the Upper Cambrian. (From Chamberlin and Salisbury's "Geology," permission of Henry Holt and Company.)

Cambrian time to the present they have steadily increased, both as regards number of species and individuals. In later geologic times the shells often attained great size. *Gastropods*, mostly of simple, low-conical types, were fairly common throughout the period (Fig. 46). The Gastropods, from their meager beginning in the Cambrian, have gone on increasing in variety of forms and number of individuals to the present, there now being fully 20,000 known species. *Cephalopods* comprise the highest class of Mollusks and Cambrian forms have been found only in Middle Upper Cambrian

strata. They were simple, straight, or curved, chamber-shelled forms. The Cephalopods became very important in subsequent periods, and the evolution of the class will be dwelt upon in succeeding chapters.

Arthropods. — Among the Arthropods the simpler forms (*Crustaceans*) only are known from the Cambrian. *Trilobites* are by far the most abundant and significant Cambrian Arthropods (Figs. 47–48). In fact they are the most important Cambrian fossils. They are the simplest and most primitive of all Arthropods, probably having evolved from a worm-like animal. They were progenitors of higher types of Arthropods. We have seen that the threefold subdivision of the Cambrian system is based upon the changes in the Trilobite fauna. Examples of the most characteristic Cambrian genera are shown in Fig. 47. They were inhabitants of the sea and they were among the most highly organized animals of the time. Trilobites persisted only till the close of the Paleozoic era, and they were especially numerous in the earlier periods of that era. The name Trilobite refers to the three-lobed character of the body. The creature possessed a distinct head-shield with compound eyes, and a more or less distinct tail-shield. Between the shields there was a highly segmented body portion. They ranged in length from an inch or less to about two feet. Nearly all of them crawled on the shallow sea bottom. "The Trilobites display an extraordinary variety in form and size, in the proportion of the head-and-tail-shields, in the number of free segments, and in the development of spines. Already in the Cambrian this wealth of forms is notable, though far less than it became in the Ordovician. As compared with those of later times, the Cambrian Trilobites are marked by the (usually) very small size of the tail-shield, the large number of free segments, and their inability to roll themselves

Fig 48

A Middle Cambrian Trilobite, *Neolemus serratus*, with well-preserved appendages (After Walcott.)

up "[1] *Eucrustaceans* of rather simple types were present, but not important. There were no real Crabs or Lobsters till much later time.

Arachnids (e.g. *Eurypterids*) are only sparingly known from the Cambrian. These forms will be discussed beyond.

No Known Land Organisms or Vertebrates. — Thus far no fossil land animals or land plants of any kind have been found,

Fig. 49

Cambrian Trilobites and other related fossils on a slab of shale from the southern Rocky Mountains of Canada Much less than natural size. (After C. D. Walcott, courtesy of the Smithsonian Institution, Washington, D. C)

and it is extremely doubtful if any, except possibly very simple land plants, did exist. Vertebrates are entirely unknown, and if any existed in the Cambrian we know, from our study of Vertebrates of succeeding periods, that they must have been of the very simplest types. These statements are of special significance in regard to the evolution of life on earth because, as far as known, all land-dwelling organisms have developed since Cambrian time.

[1] W. B. Scott: *An Introduction to Geology*, 2nd ed., p. 556.

CHAPTER VII

THE ORDOVICIAN PERIOD

Origin of Name, Subdivisions, etc.

In the preceding chapter we learned how the basal portion ot Murchison's great Silurian system came to be called the Cambrian. In 1879 Lapworth proposed to divide the remaining Silurian system into two parts, the lower portion to be called Ordovician, and the upper to retain the name Silurian. The term Ordovician was taken from an old tribe (Ordovici) which once inhabited Wales. When it is realized that one of the most profound stratigraphic breaks (unconformities) in the whole Paleozoic group lies within Murchison's old Silurian system, and between what are now called the Ordovician and Silurian systems, the justification of Lapworth's proposal is evident. In America and England the Ordovician system is now generally recognized, though on the continent of Europe the term Lower Silurian is still largely employed instead. The following tabular arrangement will serve to make clear the history of these terms:

	(*Murchison, 1835*)	(*Sedgwick*)	(*Lapworth, 1879*)
Silurian system	Upper Silurian	Upper Silurian	Silurian
	Lower Silurian	Lower Silurian	Ordovician
		Cambrian	Cambrian

Since the North American Ordovician was first carefully studied in New York state, the section there has become, to a very considerable degree, the standard to which the subdivisions in other parts of the continent are referred. During recent years several unconformities, though rather minor ones, have been discovered in the New York Ordovician, so that this section is not as perfect or continuous (stratigraphically) as was formerly supposed, certain records being entirely missing. Following are the principal subdivisions of the New York Ordovician system according to a classification by the New York Geological Survey:

CINCINNATIAN SERIES (Upper Ordovician)	Pulaski	Lorraine shale and sandstone.
	Frankfort	
	Utica shale	
MOHAWKIAN SERIES (Middle Ordovician)	Trenton limestone and shale	
	Black River limestone	
CANADIAN SERIES (Lower Ordovician)	Chazy limestone	
	Pamelia limestone	
	Beekmantown limestone.	
	Tribes Hill limestone	

The reader should not be led to think that these New York formation or stage names are the only ones now used in North America. Many other, more or less local, names have been applied either to formations (stages) found elsewhere but missing in New York, or to formations which have not yet been definitely correlated with those of New York. It is generally agreed, on the basis of priority, that when two widely separated formations become definitely correlated, the name given the formation where first studied is to be applied to both. In this way many of the New York names have come to be used over wider and wider areas. Also the kind of rock (lithologic character) making up a formation in New York may or may not be the same in other areas. Thus a sandstone or shale in New York may be replaced by a shale or limestone elsewhere, etc.

In New York, and usually elsewhere, the Ordovician strata, especially the Middle and Upper, and more especially the Trenton beds, are wonderfully rich in organic remains, and much attention has been given to the description of the fossils and the correlation of the strata. Unconformities within the Ordovician system are, relatively speaking, not very common, and they are usually not very profound. There are, however, two widespread unconformities, each representing an extensive, though short, interval of withdrawal of marine waters during the period.

DISTRIBUTION AND CHARACTER OF THE ROCKS

General Distribution. — The accompanying map (Fig. 50), shows the distribution of chiefly Middle and Upper Ordovician rocks in North America Some Lower Ordovician rocks are included with the Cambrian on the preceding map (Fig. 32), but since Lower Ordovician rarely occurs in any areas not also occupied

by the Middle Ordovician, the accompanying map shows the surface distribution of practically all Ordovician strata. By comparing the maps (Figs. 32 and 50) it will be seen that the distribution of Ordovician rocks is essentially the same as that of Upper

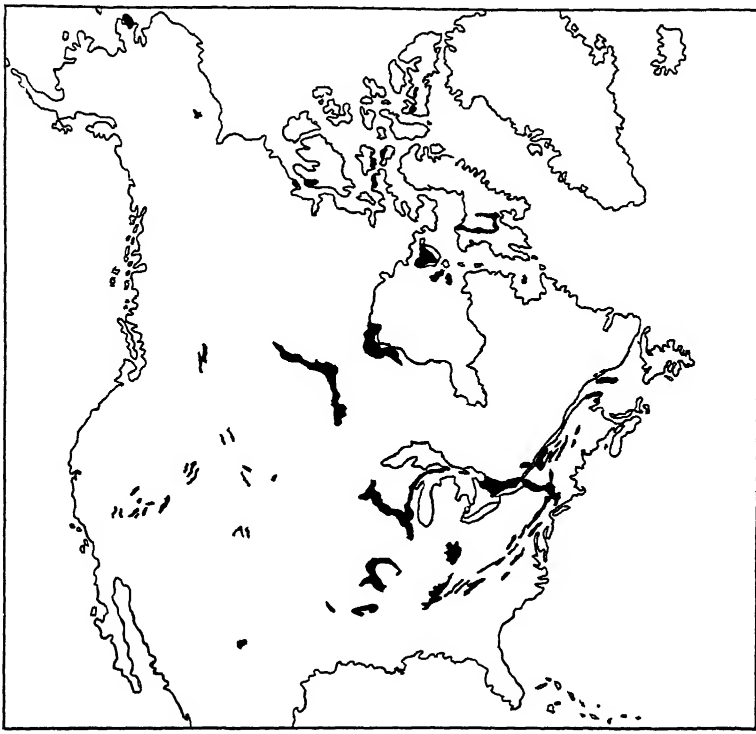


Fig 50

Map showing the surface distribution (areas of outcrops) of chiefly Middle and Upper Ordovician strata in North America (By W J M, based upon maps by Bailey Willis, U S Geological Survey)

Cambrian, with two important differences. These differences are the presence of two large areas of Ordovician west of Hudson Bay and a number of smaller areas in the Arctic Islands region.

As in the case of the Cambrian, so the surface distribution of

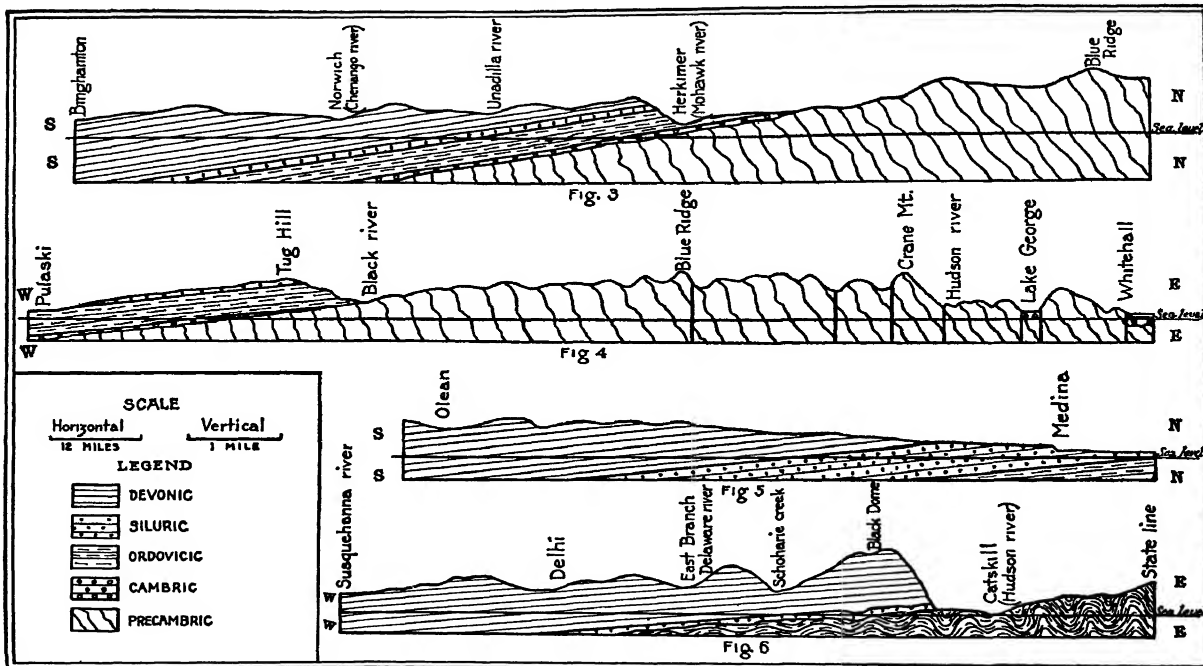


Fig. 51

Generalized structure sections through various parts of New York State, showing the attitude and relations of the various great rock systems. (After W. J. Miller, *N. Y. State Mus. Bul. 168.*)

the Ordovician rocks as indicated on this map gives no adequate idea of the former or present real extent of strata of this age, since strata have either been removed from so many districts by erosion, or are concealed under later formations, or are highly folded so that outcropping edges only are at present visible. Some regions can quite certainly be shown to have been formerly covered by Ordovician strata, as, for instance, nearly all of the Adirondack Mountain region, and a wide belt between the Great Lakes and

Fig 52

The Trenton (mid-Ordovician) limestone at its type locality, Trenton Falls, New York. (Photo by F. B. Guth, Utica, N. Y.)

Hudson Bay. Also the distribution of outcrops, together with numerous deep-well sections, conclusively prove that much, if not all, of the Mississippi Basin contains concealed Ordovician rocks. In the Appalachians, New England, and some of the western mountains extensive Ordovician strata are actually exposed only along comparatively narrow belts following the strike of the highly folded rocks. The following statements will serve to give a very general idea of the character of North American Ordovician rocks.

Lower and Middle Ordovician Rocks. — Viewed in a broad way, the Ordovician rocks (especially the Lower and Middle) are of quite different character from those of the Cambrian. Clastic

Fig 53

Trenton limestone (thin-bedded) resting upon massive Black River limestone near Boonville, New York. (Photo by the author.)

sediments, such as conglomerates, sandstones, and shales, are the dominant Cambrian sediments, while, throughout the Lower and Middle Ordovician, limestones greatly predominate (Fig. 54). Of the Lower Ordovician formations in eastern North America, the Beekmantown is one of the most widespread. It is extensively de-

System	Kind of Rock	Section	Thickness in feet
Silurian	shaly sandstone		700+
	sandstone		350 to 900
Ordovician	shale		1300 to 1800
	sandstone		2–200
	shale		1000+
	limestone		450 to 950
?	dolomitic limestone		3000 to 3500
Cambrian	shale		500 to 750
	limestone		700 to 950
	shale		200
	limestone		400+

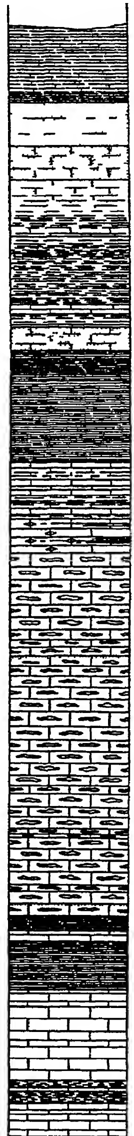


Fig 54

Geologic (columnar) section in eastern Tennessee, showing the predominance of limestone in the Lower and Middle Ordovician, and of shale and sandstone in the Upper Ordovician. (After Keith, U. S. Geological Survey, Folio 118.)

veloped in New York and in the Appalachian region. It is usually a dolomitic limestone. The other Lower Ordovician formations, due to unconformities, tend to be more locally represented.

Mid-Ordovician is generally regarded as having been one of the greatest limestone making times in the earth's history, though it should not be inferred that limestones were then universally made in the seas, because those areas of deposition close to, or receiving wash from, the lands show clastic sediments. Middle Ordovician, especially Trenton, limestones are remarkably widespread, occurring in New York, New England, New Brunswick, southeastern Canada, and near Hudson Bay, across the northern part of the Mississippi Basin, Black Hills, Wasatch and Uinta Mountains, and even in the Great Basin. The Black River formation of New York may be specially mentioned as a remarkable example of a thin formation of relatively great extent. This sheet of nearly pure, highly fossiliferous limestone, seldom if ever more than 30 feet thick, originally covered nearly all of northern New York, it since having been removed from the Adirondack region by erosion. An illustration of an exception to universal limestone-making during Trenton time is in the Mohawk Valley region of New York, where the limestone passing eastward becomes almost wholly replaced by hundreds of feet of shale Also through the Appalachians, rocks of this age contain much clastic material. The Trenton is nearly everywhere highly fossiliferous.

In the Upper Ordovician of eastern North America shales and alternating shales and fine-grained sandstones (e.g Utica and Lorraine) greatly predominate, doubtless due to rejuvenation and more active erosion of the lands probably accompanied by some shoaling of the water (Fig. 54). In the western part of the continent limestones appear to predominate, even in the Upper Ordovician.

Thickness and Metamorphism of the Ordovician. — The aggregate thickness of Ordovician strata in New York is from 2000 to 4000 feet; in the Appalachian Mountains, 5000 to 8000 feet; in the central Mississippi Valley (e.g. Missouri), 1000 feet or less; and in the Rocky Mountains several thousand feet.

Among the changes which the strata have undergone since their deposition we have mentioned their highly folded condition in certain regions, but in New England, parts of the Piedmont Plateau, and parts of the western United States the rocks are also highly metamorphosed.

Igneous Rocks. — There is no certain evidence for plutonic igneous activity during the North American Ordovician, though some granite intrusions in the Wichita Mountains of Oklahoma and some very small dikes in New York may be of this age.

A volcanic ash bed several feet thick has been found among the Middle Ordovician formations, covering several hundred thousand square miles of the southern states. The center of this volcanic action seems to have been in eastern Kentucky.

Physical History

Early Ordovician. — After the extensive emergence which caused practically all of North America to be a land area at the

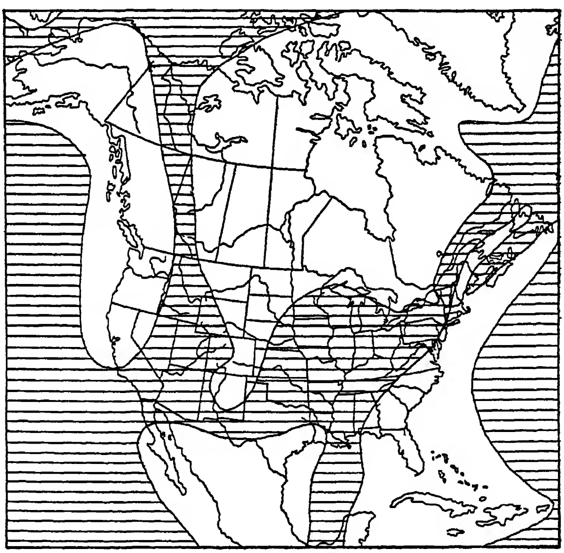


Fig. 55

Paleogeographic map of North America during Early Ordovician time. White areas, land; ruled areas, sea. (Principal data, modified by the author, from maps by C Schuchert and A. Grabau.)

close of the Cambrian, the sea began, in Early Ordovician time, to encroach upon portions of the continent. By the middle of the Early Ordovician marine waters overspread much of the Rocky

Mountain region, with Arctic and Pacific Ocean connections, the latter through Nevada and southern California, an arm of the sea extended over the Appalachian Mountain-St. Lawrence Valley areas, connecting the Gulf of Mexico with the Gulf of St. Lawrence and overspreading the eastern one-half of the Mississippi

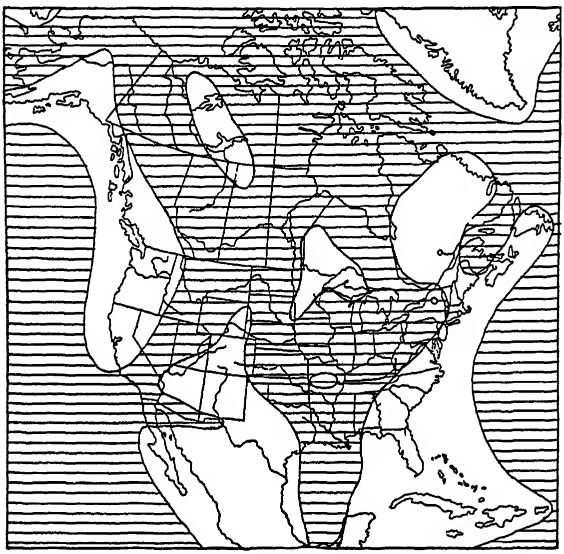


Fig 56

Paleogeographic map of North America during Middle Ordovician time. White areas, land; ruled areas, sea. (Principal data, modified by the author, from maps by B. Willis and C. Schuchert.)

Basin area; and the western and eastern seas were probably connected across the southwestern United States. Cascadia, Appalachia, and Mexicoia were well-defined land areas, as they usually were during the greater Paleozoic floods, but Canadia was very large, extending far southwestward in the United States to northern New Mexico. Map Fig. 55 shows the relations of land and water.

Early (or Lower) Ordovician time seems to have closed with a general disappearance of the marine waters from North America.

Middle Ordovician. — The outstanding feature of the Middle Ordovician physical history was the greatest known invasion of the continent by marine waters. Beginning with the continent dry land, the sea more or less gradually spread until the midst of Middle Ordovician time when the grand climax was reached as shown by map Fig. 56. At least two-thirds of the continent was submerged. The lands were low, erosion was not very active, the seas were wide, and, therefore, relatively little land-derived sediment was deposited on the floor of the widespread continental sea. It was, rather, a time unusually favorable for limestone making, and the remarkably extensive Black River and Trenton limestones were then formed. This vast sea teemed with Invertebrate forms of life, including thousands of species.

The close of Middle Ordovician time was marked by a withdrawal of the marine waters from all of the continent excepting the general Appalachian Mountain area and westward to Michigan and Arkansas.

Late Ordovician. — Late (or Upper) Ordovician time was marked by a renewed great transgression of the sea which was almost as extensive, and covered nearly the same areas, as the vast Middle Ordovician sea. This widespread sea existed during the midst of Late Ordovician time.

Since late Upper Ordovician sediments are mostly clastic (shales and sandstones), it is evident that an important change took place in the physical geography conditions toward the close of the period. Considerable portions of the sea bottom were gradually converted into dry land, and other portions were shoaled. Either an uplift of the land, or a withdrawal of the epicontinental sea waters because of sinking of the ocean bottoms (Atlantic and Pacific), or both, may be the explanation. The newly exposed lands, and the relatively higher old lands, suffered rather rapid erosion so that clastic sediments accumulated comparatively fast. As we shall presently learn, considerable crustal disturbances (orogenic), accompanied by uplifts, reached their climax toward the close of the period in eastern North America, and there is much evidence to show that such actual uplifts began well before the close of the period.

As a result of the general emergence, practically the whole of the continent became dry land at the close of the Ordovician.

Depth of Ordovician Seas. — Because Ordovician strata often

show a thickness of 2000 to 8000 feet, it should not be inferred that the Ordovician sea was necessarily ever 2000 to 8000 feet deep. The strata, even including limestones, often abundantly prove by ripple-marks, mud-cracks, and character of the fossils that they were laid down in shallow sea-water. The very character of the thick materials (original muds and sands) in the Upper Ordovician implies that they could not have been deposited in deep ocean water. Such sediments are not now forming on the deep-sea bottom. How are these statements to be harmonized with the fact that Ordovician strata thousands of feet thick exist over considerable areas? During long portions of the period the sea bottom more or less gradually subsided while stratum after stratum was deposited, and so it is not necessary to assume that the water was ever really deep. The usual depth was probably not over several hundred feet, while a depth of 1000 feet rarely if ever obtained. The North American oceans were, in other words, true epicontinental (or epeiric) seas. There were no ocean abysses at all comparable to those of the present Atlantic or Pacific where depths of three to five miles are common. This is known because no true deep-sea deposits occur in the Ordovician. The principles here set forth are applicable also to the continental seas of other periods of geological time.

Close of the Ordovician (Taconic Revolution). — The Ordovician ended with important physical or crustal disturbances, including mountain-making. All, or nearly all, of the great interior (epicontinental) sea appears to have been drained as a result of change in level between land and sea in late Upper Ordovician time. In the interior of the continent the land was only moderately elevated to remain dry only until the early part of the next period.

Thousands of feet of Cambrian and Ordovician strata accumulated in the seas which covered eastern New York, the sites of the Green Mountains and Berkshire Hills of western New England, eastern Pennsylvania, and possibly as far south as northern Virginia, including part of the Piedmont Plateau area. Toward the close of the Ordovician period, a great compressive force was brought to bear in the earth's crust upon this mass of strata. As a result of the compression, the strata were tilted, folded, and elevated above sea level into a mountain range which has been called the Taconic Range, and the physical (orogenic) disturbance

has been called the Taconic Revolution. In structure, the range consisted of a series of folds, both great and small, whose axes were parallel to the main axis of the range, that is north-northeast by south-southwest. Though we have no way of telling just how high the range may have been, nevertheless the structural features and the vast amount of erosion since the folds were produced clearly indicate that the uplift was at least some thousands of feet.

In passing westward from the main axis of the range, the folding is less and less intense, till finally the folds die out altogether.

How do we know that the Taconic disturbance took place toward the close of the Ordovician period? Strata of the next succeeding period (Silurian) rest directly in places upon the eroded edges of late Ordovician rocks; hence it is obvious that the disturbance occurred before the Silurian strata were deposited (Fig. 72). Also the disturbance doubtless began before the close of the Ordovician period. This is borne out by the fact that, for example, in central New York a distinct eroded surface at the summit of the Frankfort shales proves that region to have been dry land before the end of the period, this uplift quite certainly having been produced by the early movements of the Taconic disturbance.

In New Brunswick, Silurian strata rest upon the eroded edges of upturned Ordovician strata, and this upturning may have been coincident with the Taconic disturbance.

Sufficient lateral pressure was brought to bear in a portion of the Mississippi Basin, during the latter part of the period, to produce a long, very low arch in the rocks from southern Ohio into Tennessee. This has been called the "Cincinnati Anticline."

The late Cambrian and Ordovician connection of the interior sea with the Atlantic Ocean through the St. Lawrence Valley was closed by the disturbances toward the end of the Ordovician.

Foreign Ordovician

Map Fig. 57 gives a general idea of the relations of land and sea in Europe during the Ordovician. Also, barring certain areas from which the strata have been removed by erosion, the ruled (shaded) portion represents the present extent (surface and concealed) of Ordovician strata. There were two distinct provinces, a northern and a southern, as proved by important differences between the fossils of northern and southern Europe. Ordovician

fossils of northern Europe are closely related to those of North America, thus implying a shallow sea connection between North America and Europe. The scarcity of limestone in the European Ordovician is in marked contrast with that of North America.

In the British Isles, where the European Ordovician is thickest (being many thousands of feet), great igneous intrusions and ex-

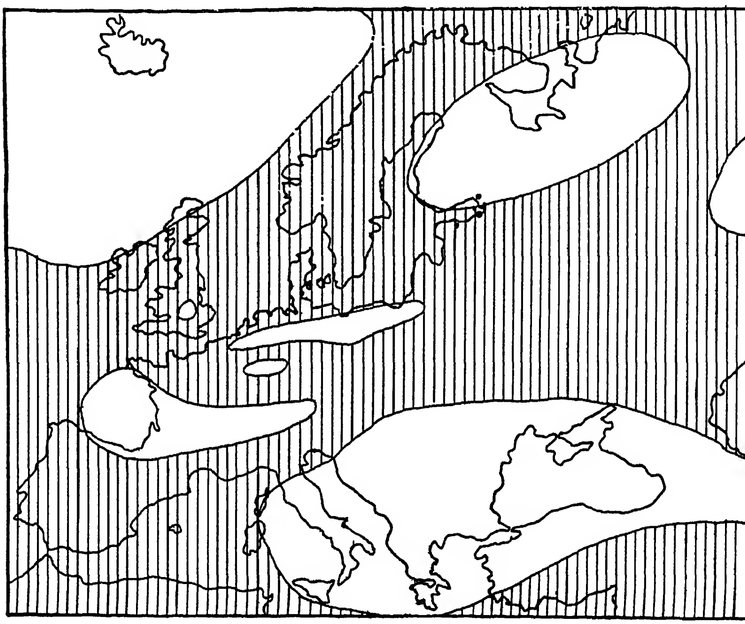


Fig 57

Paleogeographic map of Europe showing the principal areas of submergence during Ordovician time. White areas, land, ruled areas, sea. (Modified by the author after De Lapparent)

trusions took place, so that this region ranks as one of the greatest ancient volcanic areas in Europe.

As in North America, important geographic changes took place toward the close of the period, and the Silurian often rests by unconformity upon the Ordovician. In the British Isles the Ordovician rocks were folded, upraised, and often metamorphosed, with Silurian strata resting upon their eroded edges.

Ordovician rocks are also known in Peru, Argentina, Australia, Tasmania, New Zealand, Africa, India, eastern China, and northern Siberia.

Climate

Red sandstones, salt, and gypsum in the Upper Ordovician of northern Siberia clearly imply an arid climate in northern Asia during the late Ordovician. So far as can be determined from the character of the rocks, geographic conditions, and distribution of the fossils, the climate of North America and Europe must have been mild and much more uniform than now. Ordovician fossils even from Arctic lands, are very similar to those of low latitudes.

Economic Products

Many great marble quarries are located in metamorphosed Ordovician limestone in New England and the Piedmont Plateau. Also much non-metamorphosed limestone is quarried for building purposes or burnt for lime in various parts of the United States. In the Lehigh district of Pennsylvania much Trenton (argillaceous) limestone is used in the manufacture of Portland cement.

Among the greatest lead and zinc ore deposits in the world are those of the Mississippi Valley, especially in Missouri, Wisconsin, Iowa, and Illinois. These ores, which were originally disseminated through the limestones, were dissolved and redeposited in more concentrated form in openings in the rocks.

Manganese ores of Arkansas and phosphate deposits of Tennessee occur in limestones of this age.

The great oil and gas field of Ohio and Indiana derives its principal supply from the Ordovician rocks, especially the Trenton limestone. The oil and gas were formed by the decomposition of the rich organic accumulations in the limestones.

Life of the Ordovician

Abundance of Marine Life. — The Ordovician epicontinental seas literally swarmed with marine organisms, few systems containing a fuller record of marine forms than the Ordovician because of very favorable conditions of fossilization. As regards both diversity and abundance of known organisms, this period is far superior to the Cambrian. Schuchert states that over 1600 species of

animals are known from the Middle Ordovician alone. It is to be noted, however, that, with very slight exception, Vertebrate animals are not known to have existed in the Ordovician. Also our knowledge of land plants and animals is very scant. The scarcity of land organisms may have been due to prevalent oceanic conditions not favorable for fossilization, though it is also likely that land plants and animals had not progressed far or become very abundant so early in the history of the earth. Because of the unusual abundance and diversity of invertebrate animal forms in such an ancient fossiliferous system, a fuller discussion will be devoted to these forms than in succeeding chapters.

Plants. — In this period, as well as in the Cambrian, plant life of very simple types at least must have been abundant to serve as a direct or indirect food supply for the myriads of animals. Various fossil seaweeds (marine Algæ) are definitely known, especially in the Trenton series and younger Ordovician shales (Fig. 58). The rather imperfect record is doubtless due to the fact that such very simple forms were unfavorable for fossilization. Definite knowledge of land plants is lacking. In view of the abundant land flora of the Devonian, it seems more than probable that land plants existed as early as the Ordovician, and some may yet be discovered.

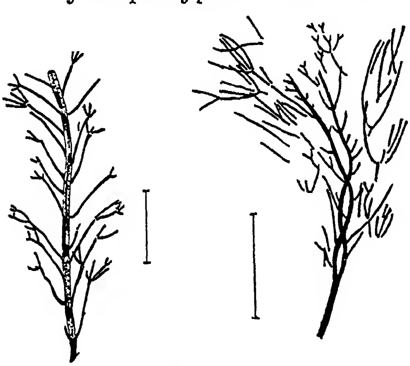


Fig 58

Ordovician Seaweeds, *Callithamnopsis fructicosa* (After Ruedemann)

Protozoans. — Both *Foraminifers* and *Radiolarians* must have been common in the seas, because in some places many fossil forms have been found. As in the preceding period, many forms without shells almost certainly existed.

Porifers. — *Sponges* were more abundant and diversified than in Cambrian time, and some were of large size. Usually only those Sponges which secreted skeletons were favorable for fossilization.

Cœlenterates. — *Hydrozoans* were abundantly represented by the *Graptolites* (Fig. 59), and in fact the Ordovician may be said to

have been the period of culmination of this remarkable, long extinct group of animals. They are so abundant and varied in Upper Ordovician shales that definite stages or horizons have been determined largely by their use. Since the Graptolites were mostly floating forms and widely distributed at a given time, they have been of great value in correlating even minor subdivisions of the system in such far separated regions as Great Britain, eastern North America, and Australia. When it is further stated that all known Graptolites are confined to the first four great fossiliferous systems (Cambrian, Ordovician, Silurian, and Devonian),[1] their

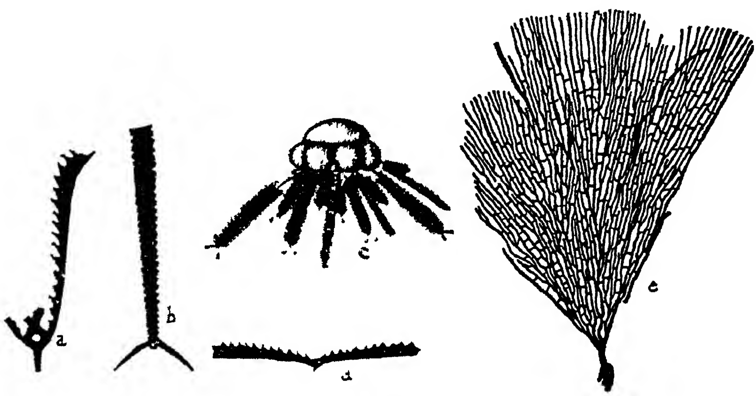


Fig. 59

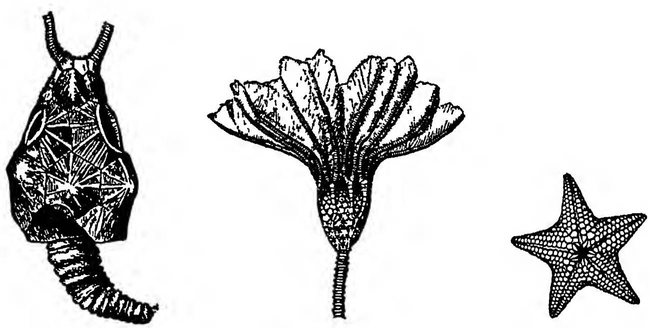
Ordovician Graptolites: *a*, *Tetragraptus fruticosus*, *b*, *Climacograptus bicornis*, *c*, *Diplograptus pristis*, *d*, *Didymograptus nitidus*; *e*, *Dictyonema flabelliforme* (*a*, *b*, *d*, after Hall; *c*, after Ruedemann; *e*, after Matthew.)

additional importance as stratigraphic indices becomes evident. In Fig. 59 the forms represent skeletons or axes of colonies, a single or a double row of protoplasmic cells having been arranged along an axis. Forms with cells on both sides of the axis were very characteristic of the Ordovician.

Anthozoans (*Corals*) were common, more especially where the mid-Ordovician limestones were forming. It will serve our purpose to divide the principal Paleozoic Corals into three groups or types as follows: (1) *Cup Corals* (solitary or compound), (Fig. 74a), (2) *honeycomb Corals* (compound), (Fig. 74b); and (3) *chain*

[1] A very few Graptolites also occur in the Mississippian.

Corals (compound), (Fig. 74c). These Paleozoic Corals were all Tetracoralla, that is, the radiating partitions (septa) of the individuals or polyps were four in number or multiples of four, while modern Corals, which first appeared in the Permian period, are Hexacoralla or Octacoralla. Modern Corals are nearly all profusely branched and the polyps are very small, while Paleozoic Corals were rarely branched and the polyps were much larger, the cup Corals usually ranging from half an inch to a foot or more in length. All three types of Corals above mentioned existed in the Ordovician, but solitary cup Corals were predominant. Compound forms, especially honeycomb Corals, were sometimes locally



a *b* *c*

Fig 60

Ordovician Echinoderms. *a*, Cystoid, *Pleurocystis filitextus*, *b*, Crinoid, *Glyptocrinus dyeri*, *c*, Asterozoan, *Paleasterina stellata* (*a*, *c*, after Billings, *b*, after Meek)

abundant. Among modern Corals the compound or colonizing forms are by far more common than the solitary forms.

Echinoderms. — All the classes of the Echinoderms were represented in the Ordovician, and all of these but the Cystoids and Holothuroids made their first appearance. *Cystoids* (Fig. 60a) reached their climax of development in this period, though they did not become extinct till the Devonian. *Blastoids* were rare and represented by very primitive forms with distinct Cystoid affinities, thus strongly indicating their derivation from the Cystoids. In fact the Blastoids assumed little importance till the Mississippian. *Crinoids* (Fig. 60b) became prominent, and, because

of their hard parts, were well suited for fossilization, though, on account of their highly segmented character, they usually fell apart after the decay of the soft parts, and consequently entire specimens are not common. *Asterozoans* (Fig. 60c), and *Echinoids* were uncommon, the latter being represented by very primitive forms. *Holothuroids* are not known as fossils but no doubt they existed because they lived before and after Ordovician time.

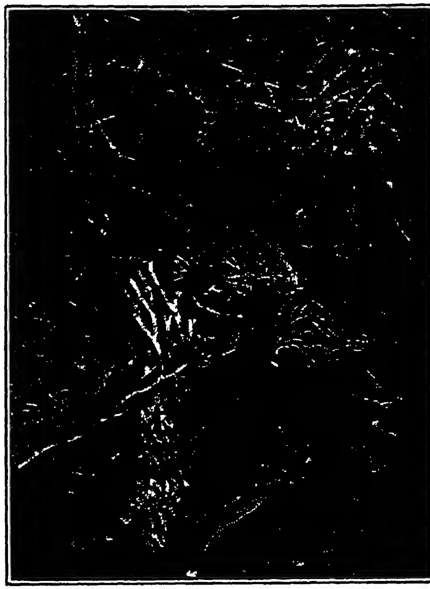


Fig. 61

Various Ordovician Bryozoans on a slab of limestone. (After R S Bassler, U. S. National Museum)

Molluscoids. — *Bryozoans* were abundant often as reef builders, particularly in the later portion of the period. Hundreds of Ordovician species are known. Though structurally (organically) very closely related to the Brachiopods, they are far different from them in outward appearance, while they look so much like the Corals as often to be distinguished from them with difficulty (Fig. 61). The Bryozoans afford a fine illustration of a class of creatures whose genera have changed very little from very ancient times to the present day.

Brachiopods became much more abundant, more varied, and more complex than in the Cambrian (Fig. 62). Those with hinged shells (Articulates) greatly outnumbered the Inarticulates for the first time. Also the shells usually were thicker and more difficult for their enemies to open because of long-hinged lines, or a fluted or ribbed structure, or both. As for the early Paleozoic in general, nearly all were straight-hinged. Many genera and species are known, certain of them having been much used in subdividing the

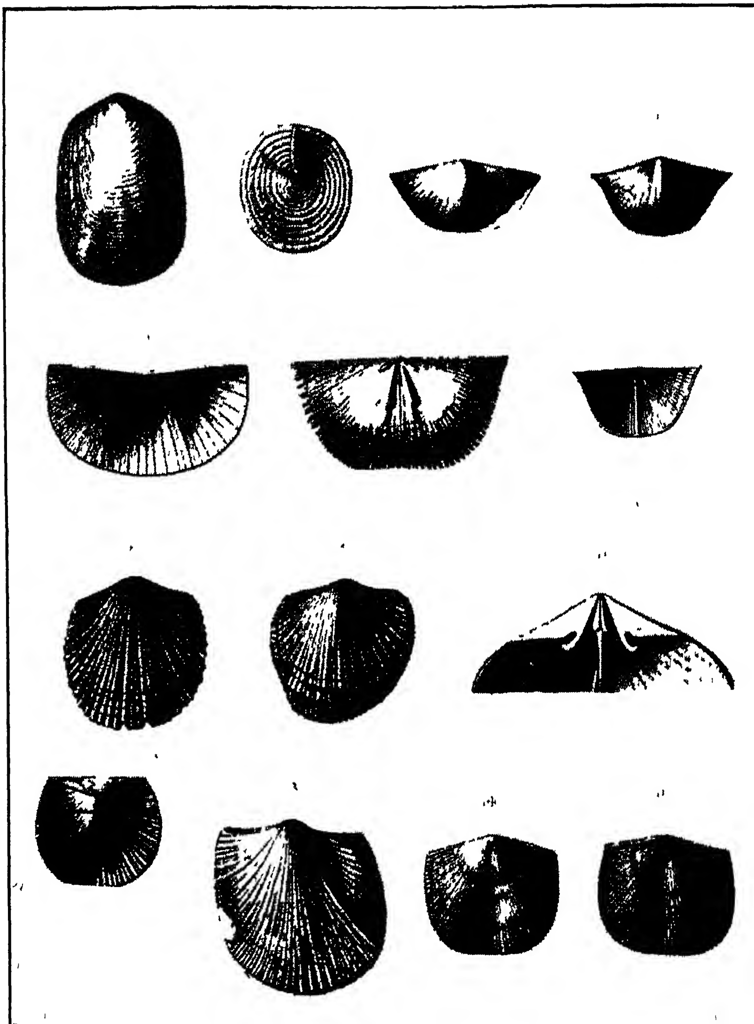
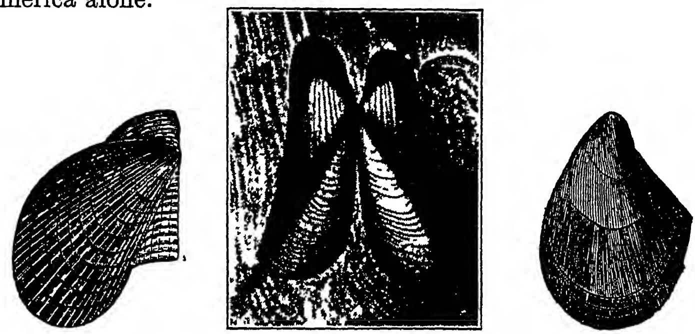


Fig. 62

Ordovician Brachiopods: *1*, *Lingula rectilateralis*; *2*, *Orbiculoidea tenuistriata*; *3*, *4*, *5*, *6*, *Plectambonites sericeus*; *7*, *Plectambonites centricarinatus*; *8*, *Plectorthis whitfieldi*; *9*, *10*, *11*, *Plæsiomys retrorsa*; *13*, *Plæsiomys porcata*, *14*, *15*, *Clitambonites americanus*. (From Ruedemann, *N. Y. State Mus. Bul. 162.*)

Ordovician system. Along with the Trilobites, the Brachiopods were the most prominent known organisms of the period. About 300 species are known from the Middle Ordovician of North America alone.



a b c

Fig 63

Ordovician Pelecypods: a, *Cardiola interrupta* (Hall); b, *Orthodesma? subcarinatum* (Ruedemann), c, *Ambonychia bellistriata* (Hall).

Mollusks. — As compared with the Cambrian, a wonderful development of Mollusks, both as regards numbers of individuals and species, took place in the Ordovician.

Pelecypod bivalves were more abundant, usually larger, and of more modern aspect than before. Typical forms are shown in Fig. 63. Ordovician Pelecypods, like their modern representatives (e.g. Clams and Oysters), appear to have thrived unusually well where muds and sands were being deposited, and they are therefore much more numerous as fossils in the Upper Ordovician shales and sandstones. One important contrast for the reader to keep in mind is the distribution of the Pelecypod bivalves through geologic time as compared with the Brachiopod bivalves. Brachiopods were very abundant and more varied than Pelecypods in the earlier Paleozoic periods, but they have steadily declined almost to extinction at the present time, while Pelecypods have steadily increased in numbers and variety to recent time.

a b

Fig 64

Ordovician Gastropods· a, *Maclurea logani* (Salter), b, *Ophileta complanata* (Vanuxem).

Gastropods, which comprise the non-chambered, univalve Mollusks, also deployed to a marked degree in this period and predominated over the Pelecypods. These Gastropods were in no essential manner different (except as to species or genera) from existing forms (e g the common Snail, and we have here another of the few excellent illustrations of an important class of animals which has shown surprisingly little change since early Paleozoic time (Fig. 64).

Cephalopods. "The largest, most powerful, and perhaps the most predaceous of the known forms of Ordovician life were the

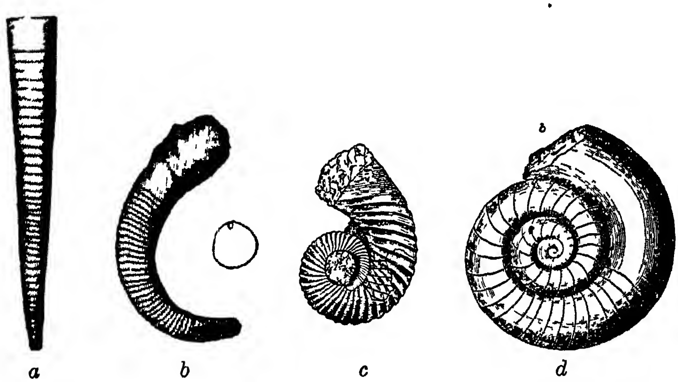


Fig 65

Ordovician Cephalopods: *a, Orthoceras sociale* (Hall), *b, Cyrtoceras neleus* (Hall); *c, Trochoceras-like* form (Silurian specimen after Barrande); *d, Trocholites ammonius* (Hall)

Cephalopods, which seem to have developed into prominence with extraordinary suddenness. Unless the Fishes, of which very little is known, contested their supremacy, they were doubtless the undisputed masters of the sea. Their relics first appear at the time of the transition from the Cambrian to the Ordovician, but they were then so far advanced and so widely differentiated from allied forms as to render it probable that they had already lived a long time. . . . The size attained by the Ordovician Cephalopods was probably never surpassed by representatives of the class. Some of the shells were 12 or 15 feet in length, and a foot (maximum) in diameter. From this great size they ranged down to or below

the size of a pipe stem."[1] These Cephalopods all belonged to the Tetrabranch or chamber-shelled subdivision of the class (Fig. 65).

The Tetrabranch Cephalopods, for two reasons, constitute one of the most interesting and instructive illustrations of evolutionary changes, ranging from the early Paleozoic to the present time, first because we have such an abundant record in the rocks of all these periods, and second because the evolutionary changes have expressed themselves in the external or shell portions in a remarkable and easily recognizable manner. The only known Cambrian Tetrabranchs were of the very simple, straight, or curved chamber-shelled types like the Orthoceras and Cyrtoceras. In the Ordovician the straight form, e.g. Orthoceras (Fig. 65a) was still dominant, but many advances were made giving rise to more curved forms (e.g. Cyrtoceras, Fig. 65b), open-coiled forms (e.g. Trochoceras, Fig. 65c), and close-coiled forms (e g. Trocholites, Fig. 65d). All of these forms belonged to the Nautiloid division of the Tetrabranchs, that is, their septa or chamber partitions, where in contact with the walls of the shell, were straight or at least very simple. Close-coiled Nautiloids of the Ordovician greatly resembled the modern Pearly Nautilus, which is one of the very few living representatives of the now almost extinct Nautiloids (Fig. 13). The persistence of these simple close-coiled forms from the Ordovician to the present is noteworthy. Ammonoids, that is to say Tetrabranchs with more complex septa junctions, appeared in the Devonian and became increasingly prominent well into the Mesozoic era, but they have not continued to the present.

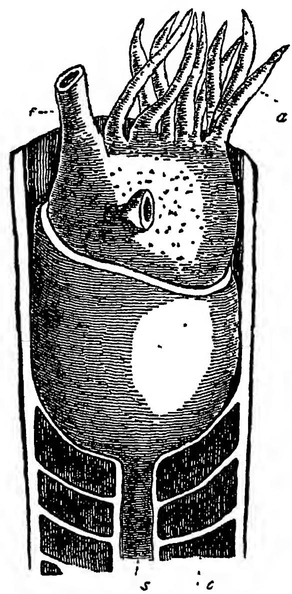


Fig 66

An Orthoceras restored. (After Nicholson, from Le Conte's "Geology," courtesy of D. Appleton and Company.)

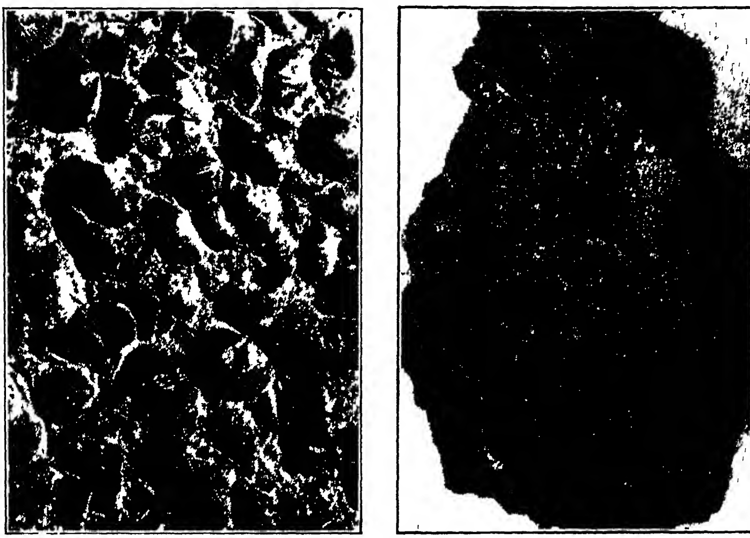
[1] Chamberlin and Salisbury. *College Geology*, pp. 525–527.

Evolution of the Chamber-shelled (Tetrabranch) Cephalopods

<table>
<tr><td>QUATERNARY</td><td>Chamber-shelled Cephalopods represented only by a few genera of close-coiled Nautiloids, e.g. modern Pearly Nautilus (Fig 13).</td><td></td></tr>
<tr><td>TERTIARY</td><td>Ammonoids very rare and in lowest Tertiary (Eocene) only</td><td rowspan="2">Close coiled Nautiloids only persist, e g. Nautilus, but more varied than now.</td></tr>
<tr><td>CRETACEOUS</td><td>Ammonoids much like Jurassic though somewhat diminished and with straight forms (e g Baculites, Fig 186), and curved or open-coiled forms more common.</td></tr>
<tr><td>JURASSIC
TRIASSIC</td><td>Ammonoids greatly advanced in numbers, species, and complexity of septa, and they reach their climax, e g Ceratite with scalloped septa (Fig. 149); Ammonite with highly frilled septa (Fig 166), and some curved and straight Ammonoids</td><td>Some Nautiloids present, but Orthoceras becomes extinct in Triassic.</td></tr>
<tr><td>PERMIAN</td><td>Ammonoids common, some showing distinctly increased (highly curved) complexity of septa (e g Waagenoceras, Fig 134).</td><td>Nautiloids, including Orthoceras, persist, but subordinate</td></tr>
<tr><td>MISSISSIPPIAN
PENNSYLVANIAN</td><td>Much like Devonian, but complexity of septa in Goniatites somewhat increased.</td><td>Nautiloids still predominate</td></tr>
<tr><td>DEVONIAN</td><td>Ammonoids first appear with only slight (angular) complexity of septa junctions, e g. Goniatite (Fig 91).</td><td>Simpler forms (Nautiloids) continue as in Silurian</td></tr>
<tr><td>SILURIAN</td><td>Much like Ordovician. No Ammonoids</td><td>Coiled Nautiloid forms predominate</td></tr>
<tr><td>ORDOVICIAN</td><td>Close-coiled forms, e.g Trocholites (Fig 65d)
Open-coiled forms, e g Trochoceras (Fig. 65c)
Curved forms, e g Cyrtoceras (Fig 65b)
Straight forms, e g Orthoceras (Fig. 65a)</td><td>Straight forms predominate.</td></tr>
<tr><td>CAMBRIAN</td><td>Straight and curved forms only.</td><td></td></tr>
</table>

Since the Tetrabranchs are of such special interest from the standpoint of evolution, the accompanying tabular summary is given to more clearly bring out certain prominent changes of shell structure from Cambrian time to the present.

Arthropods. — *Crustaceans* were represented by both Trilobites and Eucrustaceans. *Trilobites*, which were the chief Ordovician Arthropods, reached their climax or culmination of development



a *b*

Fig. 67

Bits of Ordovician sea-bottom: *a*, Brachiopod shells on limestone; *b*, Crinoid, Bryozoan, Brachiopod, Pelecypod, Gastropod, and Cephalopod remains in calcareous sandstone. (Photos by the author)

in numbers and species, more than a thousand species being known from the Ordovician alone (Fig. 68). These animals, after the Brachiopods, appear to have been among the most numerous animals of the time. Their variation in size was much like that of the Cambrian, but their eyes were usually larger and better developed. Many Ordovician forms could roll themselves up, shrimp-like, in order to protect their soft under sides. With the rise of powerful enemies, first the giant Cephalopods and then the Fishes,

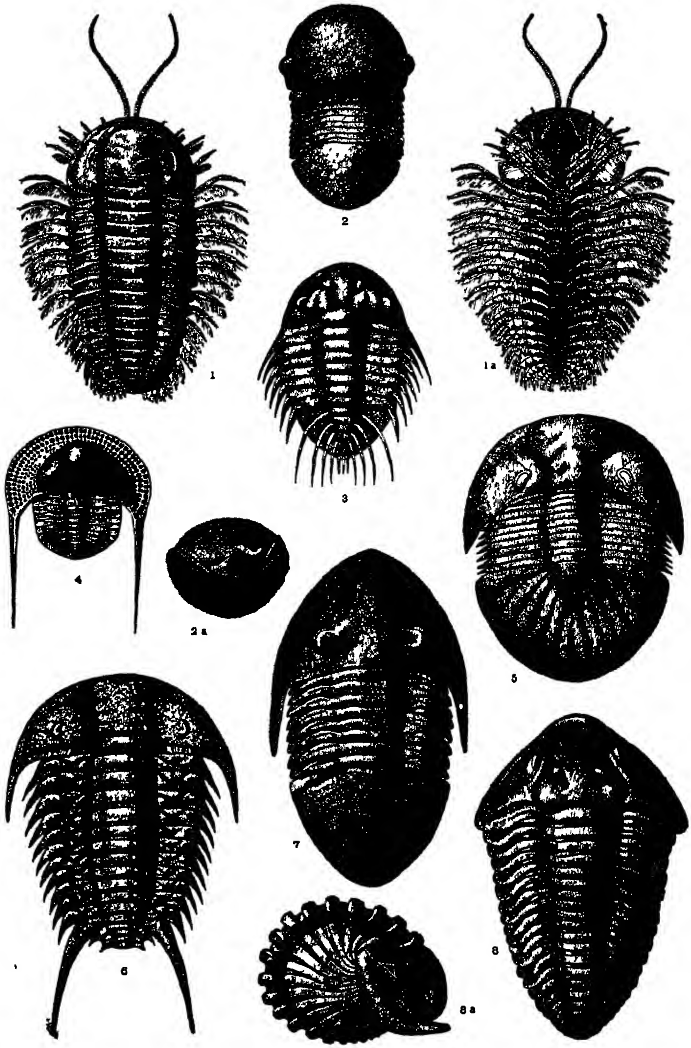


Fig. 68

Ordovician Trilobites: *1*, *1a*, *Triarthrus becki* (restorations by Beecher); *2*, *2a*, *Bumastus trentonensis*; *3*, *Acidaspis crosotus*; *4*, *Trinucleus concentricus*, *5*, *Bronteus lunatus*, *6*, *Ceraurus pleurexanthmus*; *7*, *Isotelus maximus*; *8*, *8a*, *Calymene callicephala*. (From Scott's "Introduction to G

the Trilobites declined. *Eucrustaceans* were represented by comparatively few simple forms, e.g. Ostracods and Cirripeds (Barnacles)

Arachnids, which date from Proterozoic time, were represented, though not abundantly, by the remarkable group of *Eurypterids*. Since these creatures reached a much fuller development during the Silurian period, further discussion is reserved for the next chapter.

Insects, not even in their most primitive form, existed during this period. The oldest known fossil Insects occur in Pennsylvanian rocks.

Vertebrates. — From the standpoint of evolution, perhaps the most significant feature of the Ordovician is the occurrence of the earliest known Vertebrates. These were very primitive fishlike forms such as *Ostracoderms*, which have been found in Ordovician strata at certain places in Colorado and Wyoming. The fossils are mostly very fragmentary, consisting chiefly of scales or plates, but some nearly complete dermal plates are known. They strongly suggest the Ostracoderms, but since such forms are much better known from the Devonian, we shall postpone a fuller discussion of these curious creatures.

CHAPTER VIII

THE SILURIAN PERIOD

Origin of Name, Subdivisions, etc.

We have already learned how the great body of lowest fossiliferous strata in the British Isles was called the Silurian system by Murchison in 1835. The name was derived from Silures, an old tribe which once lived in part of Wales. In the preceding chapter we have also shown how the Silurian has since been divided into three systems — Cambrian, Ordovician, and Silurian. In view of the priority of Murchison's term "Silurian," and the fact that the Ordovician strata are now known to be more important and widespread than those we call Silurian, it seems inappropriate that the terms Ordovician and Silurian are not employed in the reverse order.

Since the Silurian strata, too, were first carefully studied in New York, the section for that state becomes to a very considerable degree a standard of comparison for all American Silurian strata. Like the Cambrian and Ordovician systems, the Silurian is generally subdivided into three major portions or series, these in turn being subdivided into various stages. The most recent classification by the New York Geological Survey is as follows:

Silurian System	Cayugan series (Upper Silurian)	Manlius limestone	
		Rondout waterlime	
		Cobleskill limestone.	
		Salina shale, salt, and waterlime (also the Shawangunk conglomerate).	
	Niagaran series (Middle Silurian)	Guelph dolomite	Niagara limestone.
		Lockport dolomite	
		Clinton shale, limestone, sandstone, and iron ore.	
	Oswegan series (Lower Silurian)	Medina and Oneida sandstone, conglomerate, and shale	
		Oswego sandstone	

The New York Silurian section is more complete than the Ordovician, because the unconformities are fewer and of lesser

importance, so that few horizons are missing. As was stated in connection with the Ordovician, so here, it should be remembered that many formation or stage names have been more or less locally applied in North America to formations not yet definitely correlated with those of New York, or to a few others not represented in New York. Also the lithologic character of formations may be quite different in different regions.

Distribution and Character of the Rocks

General Distribution. — The present surface distribution of the Silurian rocks in North America is shown on map, Fig. 69, which is largely self-explanatory. Certain points of comparison with the Ordovician (see map, Fig. 50) need to be mentioned. Thus to a very considerable degree the Silurian and Ordovician rocks occur in the same areas, the chief differences being much more extensive areas of Silurian strata in the Arctic Islands region, their almost complete absence from the upper St. Lawrence Valley, and their much smaller representation in the mid-Mississippi Basin, Rocky Mountains, and Great Basin of the west.

As stated in connection with the two preceding areal distribution maps, so here, the surface distribution of Silurian rocks by no means indicates the former or even present actual extent of these rocks in North America. From many regions Silurian strata have been removed by erosion, while in other regions they are concealed under cover of later rocks. Thus most of the upper Mississippi Basin, with its essentially horizontal strata, is underlain with Silurian rocks, and only the eroded edges of upturned Silurian strata are exposed in the Appalachian Mountains.

The Oswegan Series. — This series, in the northeastern United States, consists principally of the Oswego sandstone, and Medina sandstone, shale, and (Oneida) conglomerate. Ripple-marks, cross-bedding, and the character of the fossils prove these to have been deposited in a very shallow, probably encroaching, sea The Oneida conglomerate is made up of well-rounded pebbles, bears all the marks of a typical marine-beach or very shallow-water deposit, and in central New York rests upon the eroded edges of the Upper Ordovician shales.

The Niagaran Series. — This series is of special interest both because of its lower or Clinton beds and its higher or Niagara

(Lockport and Guelph) limestones. The Clinton mostly rests conformably upon the Medina beds, but is more widespread than they.

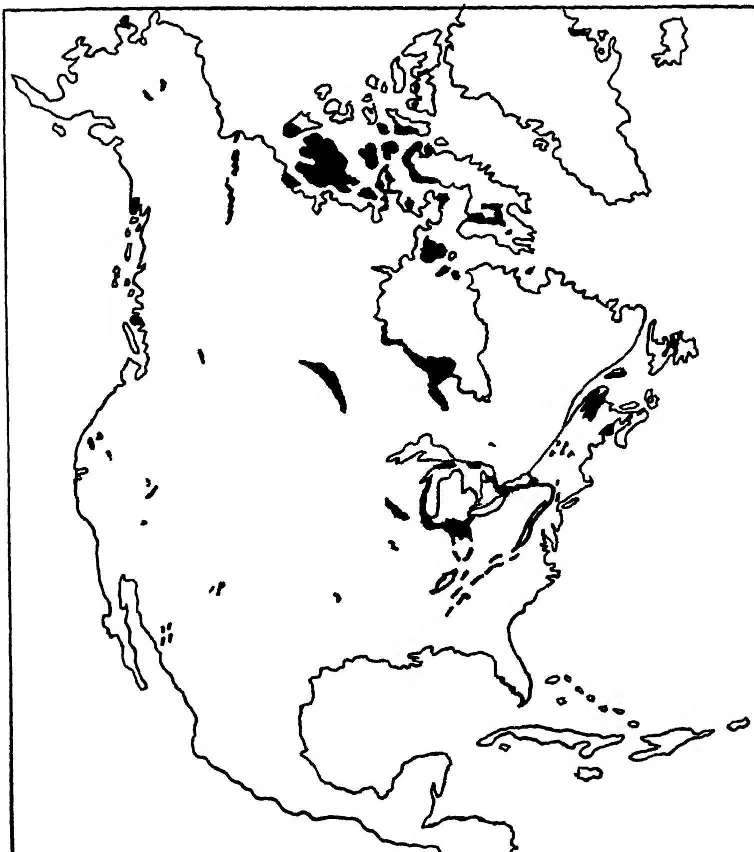


Fig 69

Map showing the surface distribution (areas of outcrops) of Silurian strata in North America. (Modified by W. J M after Willis, U. S Geological Survey)

It extends through the Appalachian Mountains, westward from central New York to Lake Huron and Indiana into Wisconsin, and probably through Illinois and Missouri. It is also known in

Nova Scotia. Lithologically this formation is quite variable, being mostly shales and sandstones in the Appalachians and central New York, and largely limestone in western New York and farther west and southwest. This limestone does not imply deep marine water, but merely shallow water comparatively free from land-derived sediments. A remarkable and well-nigh universal feature of the Clinton formation is its interstratified beds of iron ore (hematite). This iron ore is especially well developed throughout the Appalachians, from central to western New York, Wisconsin, and in Nova Scotia. The ore is concretionary or oölitic in character and apparently a contemporaneous deposit enclosed within the shales or limestones. It is often highly fossiliferous, hence the name "fossil ore."

Directly above the Clinton beds lies the Niagara limestone, which has a still wider distribution than the Clinton. Its type locality is at Niagara Falls, and in New York state it is divided into the Lockport and Guelph dolomitic limestone formations. This mid-Silurian time was another great limestone-making age almost comparable to that of the mid-Ordovician. In the United States, Niagara limestone is known throughout much of the upper Mississippi Valley and Great Lakes region, southward to Tennessee, and westward to Missouri, Oklahoma, and northern Texas. In Canada it is widely distributed in Manitoba, just west of Hudson Bay, and in the Arctic Islands. Niagara limestone also quite certainly occurs in parts of the western United States, though definite correlations are not yet made. Coral reefs are of common occurrence in the formation. It should not be understood, however, that limestone was universally forming during Niagara time, exceptions being, for example, Niagara shales in central New York and in Nova Scotia.

The Cayugan Series. — The Salina formation rests directly upon, but is much less extensive than, the Niagara formation, being found only through parts of Pennsylvania, New York, Ontario, Ohio, and Michigan. Lithologically the formation is quite variable, including all the common types of sediments as well as waterlime (hydraulic limestone), red shales, and salt and gypsum beds. The Shawangunk conglomerate, until quite recently classed with the Oneida, is of Salina age. The eroded edges of its resistant, tilted strata form the Shawangunk Ridge (so-called Range) of southeastern New York and the Kittatinny Range of

New Jersey and Pennsylvania. The Delaware Water Gap is cut through this formation (see Fig. 213).

Overlying the Salina beds, but considerably more extensive, are the limestones and waterlimes of Cobleskill, Rondout, and Manlius ages which reach from Pennsylvania and New York westward to Indiana and Wisconsin.

Silurian Rocks of the West. — Definite subdivisions and correlations of the Silurian strata of the West have not yet been made, but in certain regions, like parts of the Great Basin, there appears to be a great succession largely of limestone strata ranging in age from Middle Ordovician (Trenton) to Devonian.

Thickness of the Silurian. — From central to western New York the thickness of the Silurian system is from 1000 to 1500 feet. Its usual thickness is from 2000 to 6000 feet in the Appalachians, while in the Mississippi Valley the thickness is generally less than 1000 feet. The Niagara limestone is a notable exception to the usually greater thickness of the early Paleozoic strata in the Appalachian region, since in Wisconsin it is some 700 or 800 feet thick, while in the east it is only from 100 to 300 feet. In Maine the Silurian system contains 6000 feet of strata and thousands of feet of volcanic rocks. A thickness of about 1000 feet of Silurian occurs in central Utah, and 2500 feet in Alaska.

Igneous Rocks. — In North America volcanic igneous rocks of Silurian age occur in Maine, Nova Scotia, and New Brunswick.

Physical History

Early Silurian. — We have learned that, as a result of physical disturbance toward the close of the Ordovician, much of the interior Paleozoic sea was drained, causing the land area to be so much enlarged that it was as extensive as at any time since the beginning of the Paleozoic era. This was essentially the geographic condition of the continent at the beginning of the Silurian. The boldest topographic feature was the presence of the newly formed Taconic Range along the Atlantic seaboard.

During Early Silurian (Oswegan) time there was a more or less gradual encroachment of the sea until in the late Lower Silurian when about one-third of the continent was flooded. The relations of land and water of that time were approximately as shown by map Fig. 70.

Middle Silurian. — In Middle Silurian time the sea first with drew from Canada with the exception of the St. Lawrence regio and part of the Arctic Islands. Then a grand marine invasion se in, especially over much of Canada, reaching a climax in lat Middle Silurian (Niagaran) time. This was one of the four or fiv most extensive floods in the known history of North America About one-half of the continent was then under water. The gen eral relations of land and water, about as shown on map Fig. 71

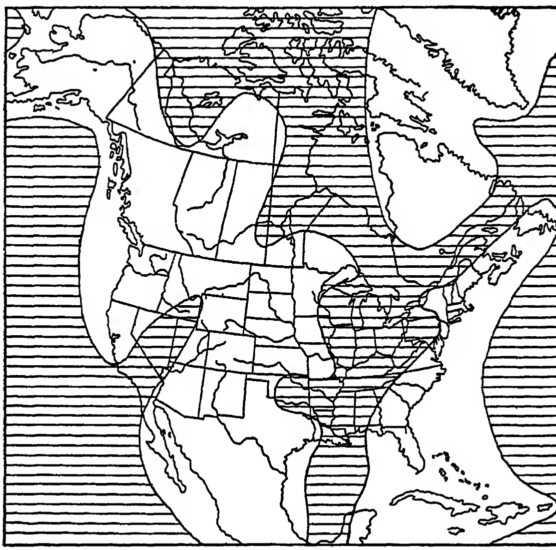


Fig 70

Paleogeographic map of North America during Early Silurian time White areas, land; ruled areas, sea (Principal data, modified by the author, from maps by C. Schuchert)

were much like those of Middle Ordovician time with the exception of the much larger Silurian land area in the central part of the continent. That this vast Niagaran sea was a shallow-water (epicontinental) sea is definitely known for reasons similar to those given in the discussion of the broad Ordovician seas.

Volcanoes were active during Middle Silurian time in Maine and parts of the St. Lawrence Basin.

Late Silurian. — Two interesting events mark the physical history of late Silurian time, namely a very considerable withdrawal of the extensive (Niagaran) sea in early Cayugan (Salina) time, and a considerable, though only partial, reextension of the sea in later Cayugan time. That a very appreciable retrogression of the Niagaran sea ushered in Salina time is proved by both the comparatively restricted distribution and the character of the Salina strata. Thus in the eastern United States and Canada

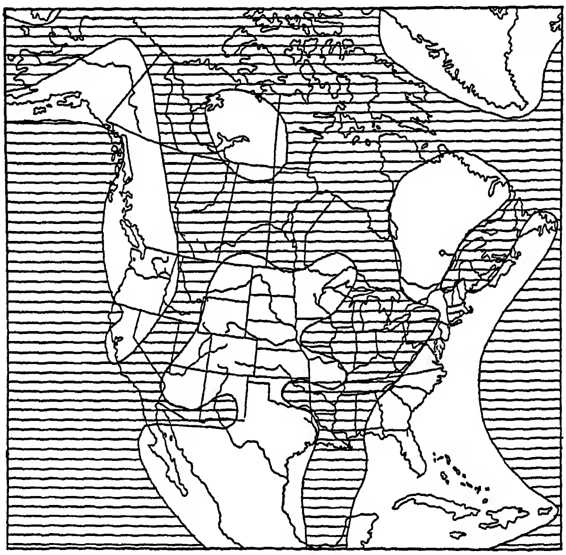


Fig 71

Paleogeographic map of North America during Middle Silurian time. White areas, land; ruled areas, sea. (Principal data, modified by the author, from maps by B Willis and C Schuchert)

Salina strata occur only through parts of Pennsylvania and southward to Virginia in the Appalachians, New York, Ontario, Ohio, and Michigan, and are quite generally characterized by red shales and sandstones, and by salt and gypsum deposits. Such materials imply arid climate conditions, with deposition in extensive lagoons or more or less cut-off arms of the sea, rather than typical open sea conditions. At the same time arms of the sea existed in the

St. Lawrence Basin, the Mackenzie River Basin, and across southern California into Nevada.

Since the immediately overlying Cayugan formations (Cobleskill, Rondout, and Manlius) are mostly marine deposits and more extensive than the Salina, it is evident that there was at least a partial restoration of more widespread marine waters in the eastern United States during later Cayugan time. This later Cayugan sea spread from eastern New York westward over the Salina lagoon

Fig 72

Early Upper Silurian (Shawangunk) conglomerate resting by unconformity upon Ordovician shale near Otisville, New York. (After New York State Museum.)

areas and into eastern Wisconsin, and from eastern New York southward through the Appalachian district The St. Lawrence and California-Nevada arms of the sea still persisted. So far as known the rest of the continent was dry land.

In addition to these broader and more important geographic changes during the Silurian period, there were of course various minor and generally local changes of relative level between land and sea, some of these now being known and some not yet determined.

Close of the Silurian. — At the close of the Silurian, or opening of the Devonian, the Cayugan sea withdrew from the area from central New York to Wisconsin, and but few comparatively small

areas of North America were submerged, as shown on map (Fig. 81). This was essentially the geography of the continent in earliest Devonian time, and it is discussed in the next chapter.

There appear to have been no mountain-making (orogenic) movements, and no important epeirogenic disturbances at the close of the Silurian in North America. Because of the comparatively quiet and gradual transition into the succeeding period, the Silurian and Devonian systems are usually not sharply separated from each other, and often, as in New York and in the Appalachian region, there has been difficulty in satisfactorily dividing the systems.

Foreign Silurian

The Ordovician division of Europe into two great provinces or basins of deposition — northern and southern — was continued in

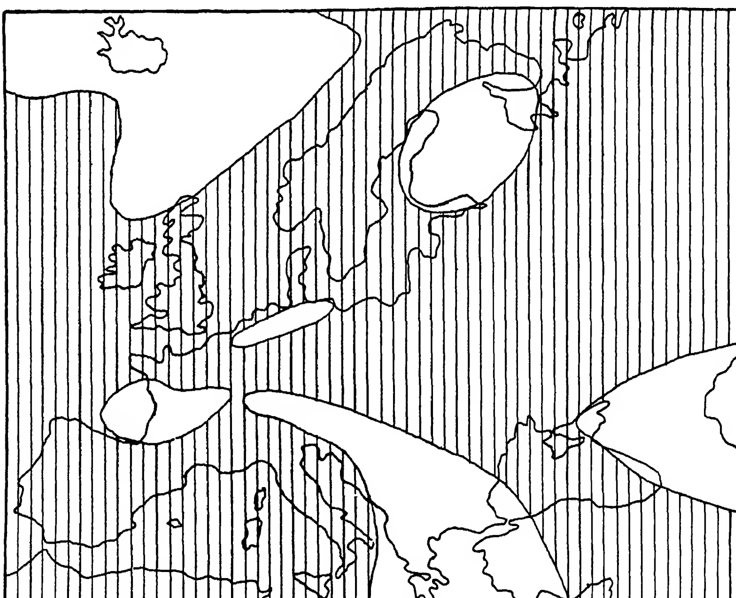


Fig 73

Sketch map showing the relations of land and water in Europe during Middle Silurian time White areas, land, ruled areas, sea (Modified by the author after F X Schaffer)

the Silurian, though the latter strata are not so widely distributed. The faunas of these two provinces show greater differences than does the northern province as compared with North America, or even other continents. This implies a lack of free communication between the southern European province and the more typical Silurian provinces of the earth.

As in America, European Silurian strata are largely concealed beneath later formations. Usually the Silurian rests conformably upon the Ordovician, except in the British Isles. Also in most of Europe the transition to the Devonian was gradual, except in the British Isles, where the Silurian strata were tilted and eroded before the deposition of the Devonian. In much of the southern province the rocks are folded and tilted, though this deformation took place sometime after the close of the Silurian. In mid-Silurian, as in North America, much limestone was formed across the British Isles, southern Scandinavia, and well into Russia. Silurian strata of Europe are not as thick as those of the two immediately preceding systems, being from 3000 to 5000 feet in the British Isles, and generally less elsewhere. Igneous rocks of Silurian age are almost unknown.

In other continents Silurian rocks have seldom been well studied and separated from the Ordovician, though they are definitely known in China, Africa, Australia, and South America.

Climate

The general distribution and character of the rocks and their fossil content point to more uniform climatic conditions than those of today. Fossils in the Arctic Silurian rocks are not essentially different from those of low latitudes.

From central New York across to Michigan at least, there was an arid climate during the Salina epoch, as already mentioned, but this was probably only local.

Economic Products

Silurian sandstones and limestones are extensively quarried for building purposes, or the limestones burned to make quick-lime. The waterlimes of late Silurian age were until quite recently considerably used for the manufacture of hydraulic cement, especially in the Hudson Valley of New York state.

We mentioned the widespread and almost universal occurrence of hematite iron ore in the Clinton formations. This ore is mined to some extent in central and western New York, but in the Birmingham, Alabama, district, which is the second greatest iron mining region of America, the Clinton formation is the source of the ore.

Another important economic product of Silurian age is the salt of the Salina formations. In New York alone salt beds underlie most of the western part of the state or an area of about 10,000 square miles. Sometimes there is one bed and sometimes several interstratified with other rocks. Single beds locally attain a thickness of from 50 to 80 feet. In the southern part of the state the salt is most deeply buried under later rocks, a well at Ithaca having passed through 248 feet of salt in seven beds below 2244 feet from

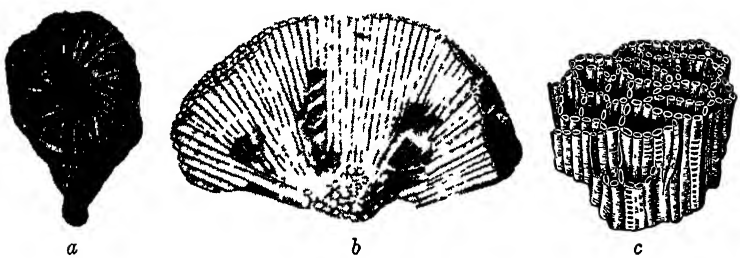


Fig 74

Silurian and Devonian Corals *a*, Cup-coral, *Zaphrentis roemeri* (M Edwards and Haime) (Devonian form); *b*, Honeycomb-coral, *Heliolites pyriformis* (Guettard); *c*, Chain-coral, *Halysites catenulatus* (Linn)

the surface. Toward the north the beds gradually come near the surface. Important salt beds also occur near Cleveland, Ohio, and Detroit, Michigan. The usual method of obtaining the salt is by pumping brine from deep wells, and then evaporating.

Much gypsum is mined along the lines of outcrop of Cayugan strata in western New York.

Oil and gas are obtained from the Clinton sandstone of Ohio, and some gas from the Medina sandstone of New York.

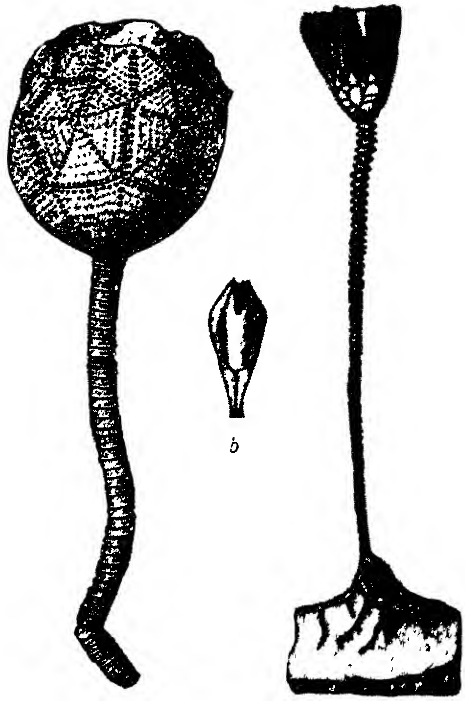
Life of the Silurian

Plants. — *Sea-weeds*, though not abundant as fossils, are well known, especially in the Medina-Oneida sandstones and con-

glomerate, and Clinton formation, all of which were deposited in very shallow water. Knowledge of the land plants of the period is still very meagre, though some rather doubtful specimens, such as mosslike forms, are known. Perhaps the most authoritative example is a fossil fernlike plant from France, which shows that the Pteridophytes at least were in existence. Considering the profuse land vegetation of the next (Devonian) period, it seems certain that their progenitors must have been well represented in the Silurian, and that either their remains may yet be discovered, or the conditions for their preservation were unfavorable.

Protozoans have not been found as fossils, but they must have existed, because they are known from both the preceding and succeeding periods.

Porifers. — *Sponges* were common, and in the Silurian strata of western Tennessee they are exceedingly abundant. A genus of nearly spherical forms with deep grooves was particularly prominent.



a b c

Fig 75

Silurian Echinoderms: *a*, Cystoid, *Caryocrinus ornatus*, *b*, Blastoid, *Troostocrinus reinwardti*, *c*, Crinoid, *Eucalyptocrinus crassus*. (After Say, Troost, and Hall respectively)

Cœlenterates. — *Graptolites*, though greatly diminished in importance, were still fairly common. The more complex colonies, such as branching forms and those with double rows of cells on their axes, were nearly extinct, the simple forms mostly only remaining.

Anthozoans (Corals) increased in prominence to a very notable degree, and the simple *Cup Corals* (Fig. 74a) of the Ordovician were superseded in importance by the colonizing or compound forms. *Chain Corals* (Fig. 74c), which were rare in the Ordovician, reached their climax of development, but became nearly extinct by the close of the period. *Honeycomb Corals* (Fig. 74b) were also common.

Echinoderms. — Though the *Cystoids* reached their climax in the Ordovician, they were still abundant in the Silurian, the Ni-

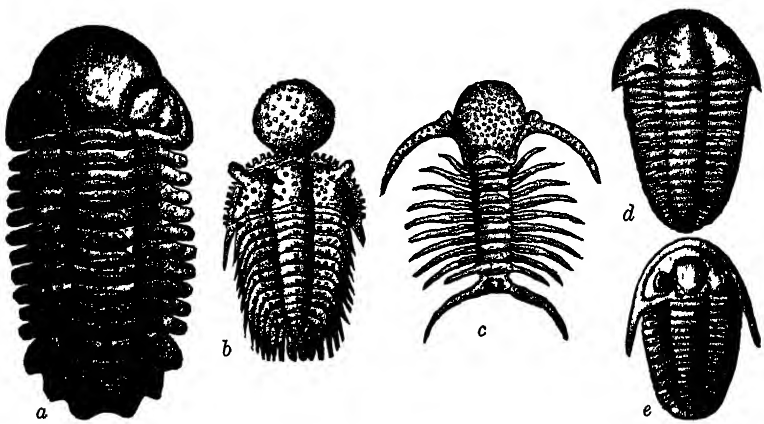


Fig. 76

Silurian Trilobites: *a, Sphærexochus mirus* (Bey.); *b, Staurocephalus murchisoni* (Barr.); *c, Deiphon forbesi* (Barr.), *d, Calymene niagarensis* (Hall), *e, Cyphaspis christyi* (Hall) (From Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

agara limestone near Chicago being particularly rich in them. Many were unusually large, and some showed greater degree of symmetry in arrangement of plates than before (Fig. 75a).

Blastoids still remained rare, only two genera being known (Fig. 75b).

Crinoids very considerably increased in numbers and species as well as in complexity of structure (Fig. 75c). "They attained such abundance in certain localities that their fragments formed the main substance of the limestone. These spots became veritable 'flower-beds' of 'stone lilies,' and certain localities, as Lockport, N. Y., Waldron and St. Paul, Ind., Racine, Wis., Chicago, Ill.,

Gotland, Sweden, and Dudley, England, have become noted as peculiarly rich crinoidal fields, where beautiful and varied forms

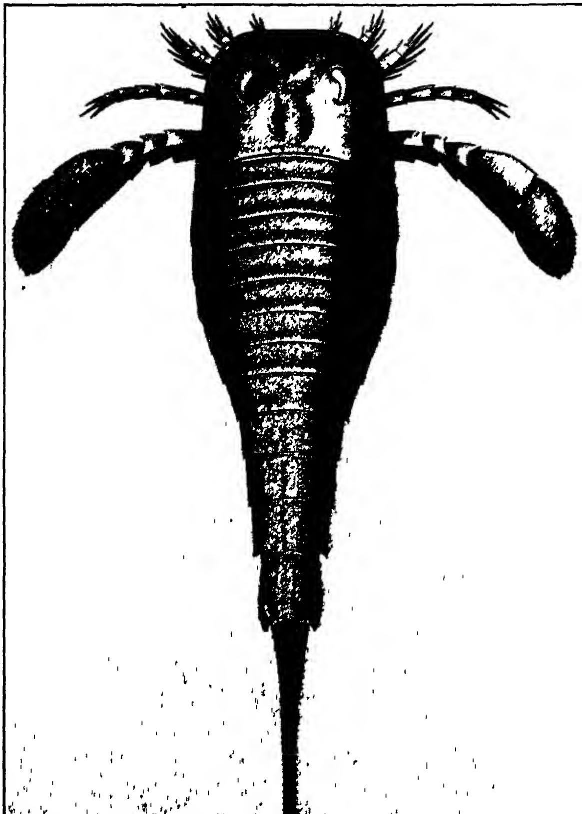


Fig 77

A Silurian Eurypterid, *Eurypteris remipes*, restored to show dorsal side. (After Clarke and Ruedemann, N. Y State Mus. Mem. 14.)

grew in groves, as it were."[1] About 400 species are known from the Silurian of North America.

Asterozoans (Star-fishes) and *Echinoids* (Sea-urchins) became

[1] Chamberlin and Salisbury. *Geology*, Vol 2, p. 400.

more common, though by no means abundant. Modern Sea-urchins have exactly twenty rows of calcareous plates tightly fitted together, while Paleozoic forms had a variable number of plates, and in some forms the plates were only loosely joined together, this latter feature apparently being a primitive characteristic.

Fig 78

A Silurian Scorpion, *Paleophonus caledonicus*, by Hunter after Peach (From Le Conte's "Geology," permission of D. Appleton and Company)

Molluscoids. — *Bryozoans* were less prominent than in the Ordovician, but, nevertheless, they were often common as reef builders. Their lack of abundance may be somewhat apparent only, due to the fact that more delicate forms prevailed.

Brachiopods continued to be the most prominent of all organisms as regards both number of individuals and species, and this in spite of the fact that very few Ordovician species, and not many genera, continued from the Ordovician into the Silurian. Two genera, Spirifer and Pentamerus, made their first appearance and were especially prominent in the Silurian, but became even more so in the Devonian. The Spirifer developed a long, straight, hinge line, while the Pentamerus had a sort of hook-shaped beak projecting over the hinge line.

Mollusks. — The *Pelecypods* and *Gastropods* were still common, but they were in no important way different from those of the preceding period.

Cephalopods were represented only by the Nautiloids. Of these, the straight (Orthoceras) forms were still common, but the curved and coiled forms became predominant. Some of the Nautiloids were notably ornamented externally. Otherwise, except

for many genera and species changes, the Cephalopods were much like those of the Ordovician, which are rather fully discussed.

Arthropods. — *Crustaceans* were represented by Merostomes, Trilobites and Eucrustaceans. *Horse-shoe Crabs*, representing the *Merostomes*, first appeared in the Silurian. *Trilobites* culminated in the preceding period, but they still continued to be common. A few new genera appeared, but more disappeared. Silurian Trilobites were perhaps more diversified than in any other period.

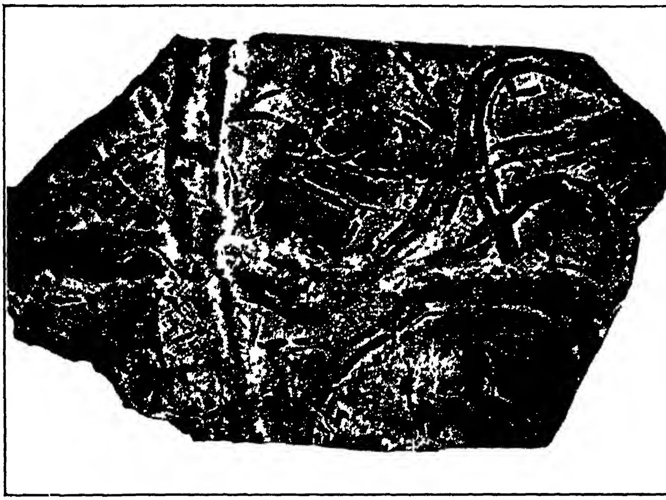


Fig. 79

Animal tracks on Silurian sandstone from Clinton, New York
Length of specimen, 10 inches. (Photo by the author.)

"Like the decadent nations revealed to us in human history, they indulged in extravagant and futile eccentricities, ill befitting their approaching overthrow. Odd and highly ornate forms appeared in profusion (Fig. 76b, c), and in most instances the spines, tubercles, and horns which they produced seem to have had little or no real value in their life activities. We shall see in studying later periods that similar eccentricities mark the fall of other groups, such as the Ammonites and the Reptiles."[1] *Eucrustaceans* were much like those of the Ordovician.

[1] Blackwelder and Barrows. *Elements of Geology*, pp. 352–353.

Arachnids, represented by the *Eurypterids*, greatly increased in numbers, species, and size, and they appear to have culminated in this period. The following brief description, together with an examination of Fig. 77, will serve to give a fair idea of the appearance and structure of these remarkable creatures. In the typical Eurypterid, a quadrate or semicircular head has behind it twelve movable segments making up the abdomen, and attached to the last segment is either a spine or plate-like tail. The five pairs of appendages all come out from the head portion, thus being markedly different from the Trilobites. The first pair of appendages are much enlarged, sometimes provided with pincers and sometimes not, while the fifth pair are usually long and they serve as swimming paddles. They varied greatly in size, one species, from the Silurian, having attained a length of over six feet and so is one of the largest known Arthropods. Many Eurypterids appear to have been marine animals, while others probably lived in fresh or brackish water lagoons. The Arachnids included also the earliest known *Scorpions* (Fig. 78), which were in many respects similar to the Eurypterids. These Scorpions are to be classed among the very early, if not earliest, definitely known land or air-breathing animals to inhabit the earth.

Vertebrates. — The only known Silurian Vertebrates were of very simple types, such as the *Ostracoderms* and primitive *Fishes*, probably *Sharks*. All of the Ostracoderms were small, odd-shaped creatures, but rather closely related to the more prolific Devonian forms to be described later.

When we consider the fact that fully one-half of known geological time had passed before the close of the Silurian, it is a remarkable fact, from the standpoint of evolution, that Vertebrate life had made not more than a meagre beginning by Silurian time. This fact is even more impressive when we realize something of the tremendous advances made by the Vertebrates and the great variety of their forms which have inhabited the earth since Silurian time, as outlined in the following pages of this book.

CHAPTER IX

THE DEVONIAN PERIOD

Origin of Name, Subdivisions, etc.

In 1839 Sedgwick and Murchison gave the name of Devonian to strata in the county of Devonshire in England where rocks of this age were first carefully studied. Because of the metamorphosed and highly disturbed character of the English Devonian, the sub-divisions in Europe were not well worked out until the more undisturbed rocks of Belgium and along the Rhine were studied.

In North America the New York subdivisions are taken as the standard, because the Devonian strata were first carefully studied there. The New York Devonian section is a remarkably complete one of very considerable thickness (fully 4000 feet), with not a single stage missing, except possibly the very lowest one, and with a surface distribution over fully one-third of the area of the state. There was practically continuous deposition of strata during Devonian time in New York, and if locally a stage or sub-stage is missing, it is present elsewhere in the state. It is doubtful if a greater degree of refinement of knowledge exists regarding so complete a section of the Devonian or of any other Paleozoic system in North America than that in regard to New York state.

The latest classification of the New York Devonian system by the State Geological Survey follows:

Upper Devonian	Chautauquan series	Chemung and Catskill sandstones.
	Senecan series	Portage sandstones and shales. Genesee shales. Tully limestone.
Middle Devonian	Erian series	Hamilton shales and limestone. Marcellus shales and limestone.
	Ulsterian series	Onondaga limestone. Schoharie grit.

LOWER DEVONIAN	Oriskanian series	Esopus grit
		Oriskany sandstone and Glenerie limestone
		Connelly conglomerate
		Port Ewen limestone
	Helderbergian series	Becraft limestone
		New Scotland limestone.
		Kalkberg limestone
		Coeymans limestone

For a long time the Helderbergian series was placed with the Silurian system, but on the basis of careful study of its fossils, it is now generally agreed that it really represents the lowest portion of the Devonian system. This is a good example of the difficulty in drawing the line between two systems when no sharp stratigraphic break or unconformity exists.

As stated in connection with the preceding system, so here the reader should know that in many parts of America where definite correlations have not been made, local subdivisions or stage names are employed, and also that the lithologic character of the various stages in New York may be quite different from those in other regions.

DISTRIBUTION AND CHARACTER OF THE ROCKS

General Distribution. — The map (Fig. 80) gives the surface distribution of all known Devonian rocks in North America. A comparison with the Silurian strata map (Fig. 69) will show that, in the eastern part of the continent, these two rock systems are very similar in distribution, though the Devonian is absent from Newfoundland and is of much larger surface extent in New York. As compared with the Silurian the only other important differences are the much larger Devonian area in the Mackenzie River region and the much smaller areas in the Arctic Islands region.

It should again be borne in mind that these surface areas of Devonian rocks fall far short of indicating the actual former, or even present extent of rocks of this age, because considerable Devonian rock has been removed by erosion, and much is now buried under later formations. Thus in the Appalachians and the mountains of the western United States, the Devonian strata

have been highly folded with others, so that only the outcropping edges are visible. In the Mississippi Basin, where the strata are essentially horizontal, deep well borings have proved that the Devonian strata are extensively distributed under cover of later rocks.

Lower Devonian Rocks in the East. — The *Helderbergian* series is very limited in its distribution, and is found almost wholly in eastern North America in three regions: (1) Maine, eastern Quebec, Nova Scotia, and New Brunswick; (2) the northern and middle Appalachians; and (3) in the lower Mississippi Valley in Oklahoma, southeastern Missouri, and western Tennessee and Kentucky. Limestone almost everywhere makes up the series which ranges in thickness up to 600 feet.

The *Oriskanian* series is chiefly represented by the Oriskany sandstone, the other members of the series being only of mere local importance. The Oriskany formation is extensively developed from central New York southward through the Appalachian region to Alabama, and in the eastern Mississippi Valley. Its thickness varies from a few feet in New York, to several hundred feet in western Maryland. In northern Maine, New Brunswick, and Nova Scotia, the Oriskany (much of it limestone) is well developed though not much studied.

Middle Devonian Rocks in the East. — The *Ulsterian* rocks, except the Schoharie grit which is limited to eastern New York, are much more extensive than the Lower Devonian.

The *Onondaga* limestone formation extends from eastern New York and Pennsylvania westward to northern Michigan and southern Illinois, except over the Cincinnati anticline area Its entire absence from all but the northern portion of the Appalachians is particularly noteworthy. Its thickness is seldom over 200 feet, and it is often largely made up of Corals, as for example at the Ohio River rapids near Louisville. In northern Maine, New Brunswick, and Nova Scotia, the Onondaga limestone is widespread and apparently many hundreds of feet thick. It also occurs at the south end of Hudson Bay.

The *Erian* series, represented by the Hamilton and Marcellus shales and limestones, has very much the same distribution as the Onondaga, except for the absence of Erian from the south end of Hudson Bay, and additional Erian areas in the middle Appalachians, Iowa, northern Missouri, and just west of Lake Winnipeg.

In the east, shales were deposited, attaining a thickness of 1500 to 5000 feet in Pennsylvania, while in the upper Mississippi Basin,

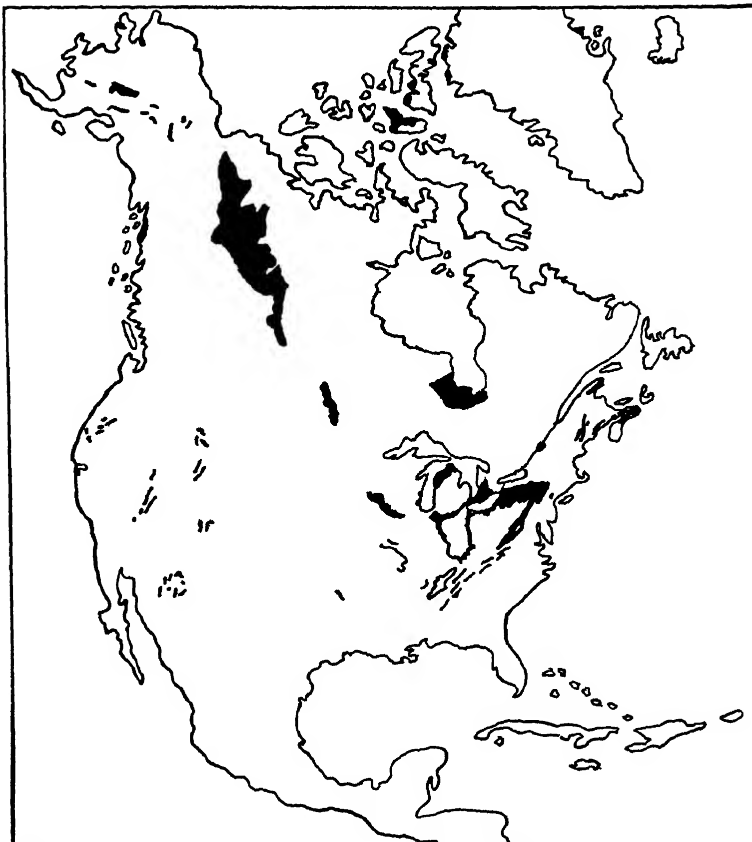


Fig. 80

Map showing surface distribution (areas of outcrops) of Devonian strata in North America. (Modified by W. J. M after Willis, U S Geological Survey)

where much limestone still formed, its thickness is notably less. A good idea of the distribution (surface and concealed) of the Middle Devonian rocks is afforded by noting the water areas on the

paleogeographic map (Fig. 82), though from these areas some Devonian strata have been removed by erosion.

Upper Devonian Rocks in the East. — These show a distribution very similar to the Middle Devonian, except that the southern Appalachians and region immediately westward also contain them. Leaving out the area of Onondaga at the south end of Hudson Bay, a good conception of the distribution of the Upper Devonian rocks may be gained by examining the map (Fig. 82), because almost everywhere that any Devonian is present, the Upper Devonian also occurs.

The *Senecan* series, except for the comparatively thin and local Tully limestone, consists of the Genesee shales, and Portage sandstones and shales. The Genesee ranges in thickness from a few feet in western New York, to several hundred feet in central Pennsylvania, while the Portage is over 1000 feet thick in western New York.

The *Chautauquan* (Catskill[1] and Chemung) series of sandstones have a thickness of 1000 to 1500 feet in western New York; 3000 feet in eastern New York; and a maximum of 8000 feet in eastern Pennsylvania. The Catskill was quite certainly mostly a fresh or brackish water deposit.

In the Mississippi Valley, westward from New York and the Appalachians, the Upper Devonian is much thinner; subdivisions are not so well represented, or recognized; and the New York names have not been applied.

Devonian Rocks in the West. — Lower Devonian strata, largely limy, occur in Nevada, eastern California, and Kennedy Island west of northern Greenland. Middle and Upper Devonian strata, mostly limestones, are extensively developed in western North America within the areas represented as covered by the sea in map Fig. 82. The Devonian of the west has only here and there been studied in detail

Comparison of Ordovician, Silurian, and Devonian Systems. — "Comparing the rocks of the Ordovician, Silurian, and Devonian, as these are developed in the Appalachian and adjoining regions, a certain rhythmic or periodic recurrence of events may be discovered among them. Each system is characterized by a great and very widespread limestone formation, the Trenton, Lockport-

[1] The Catskill is essentially an eastern phase of the Chemung in New York.

Guelph (Niagara), and Onondaga (Hamilton), respectively, and in each the limestone is succeeded by shales or other clastic rocks, the Utica, Salina, and Portage (respectively), due to an increase of terrigenous material, and each was closed by a more or less wide-spread emergence of the sea-bottom. Each began with a subsidence which gradually extended to a maximum at the time when the great limestone was formed. The parallelisms are not exact, but they are certainly suggestive."[1]

Thickness of the Devonian. — In the northern Appalachian Mountains the Devonian system attains a maximum thickness of some 14,000 or 15,000 feet. In the southern Appalachians the thickness is usually less than 1000 feet. In New York state the system has a thickness of 4000 to 7000 feet. Over much of the upper Mississippi Valley the thickness is generally less than 1000 feet, though rather locally, in Ohio, a thickness of fully 3000 feet is reached, 2600 feet of this being Upper Devonian shales practically equivalent to the Portage and Chemung beds of the east. In Nevada the system appears to show 6000 feet of limestone and shale. In Utah the system reaches a thickness of about 5000 feet.

Igneous Rocks. — For Devonian time, as for the earlier Paleozoic periods, the evidence indicates relatively little igneous activity. The greatest scene of activity was in New England, New Brunswick, Nova Scota, and eastern Quebec where many sheets of lava are interbedded with Devonian strata, and where considerable masses of granite magma were intruded. Devonian lavas are also known in northern California.

Physical History

Early Devonian. — In earliest Devonian (Helderberg) time most of North America appears to have been dry land Inspection of the paleogeographic map (Fig. 81) of that time shows that marine waters occupied a long, narrow area in the east This sound covered the sites of the Appalachian Mountains, western New England, and the St. Lawrence Basin, connecting the last named region with the Gulf of Mexico. It was much like the Early Cambrian sound in the same region. Since the Helderberg formation is chiefly limestone, the waters were clear and this implies no adjacent high lands, or at least no rapid erosion. In the west an arm of the sea must have reached

[1] W. B. Scott: *An Introduction to Geology*, 2nd ed , pp. 577–578

into the Nevada Basin as proved by the Helderberg limestone there, the connection with the Pacific probably having been across California as suggested by the later geographic conditions (see Fig. 81). Part of the Arctic Islands region was submerged, as well as a little of southern Alaska.

The Oriskany sea was more widespread and covered the whole Appalachian region from central New York to Alabama and westward over much of the eastern upper Mississippi Basin, except probably the Cincinnati anticline area. Nova Scotia-New Brunswick remained submerged. The sharp change to deposition of coarse, clastic sediments argues for considerable land rejuvenation, or much more rapid erosion, or both. The sediments are of distinctly shallow-water character, and the fossils show the fauna to have been suited to such conditions. The fossils are remarkably similar

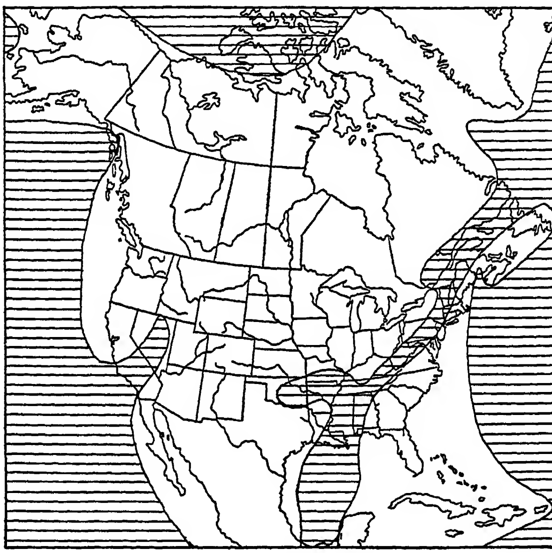


Fig 81

Paleogeographic map of North America during early Lower Devonian time. White areas, land; ruled areas, sea (Principal data, modified by the author, from maps by C Schuchert.)

to those of the same age (Coblenzian) in Europe from which region they appear to have migrated. "The evidence then is fairly conclusive that during the period represented by the Coblenzian Oriskany, the arenaceous epicontinental sediment was the ground traversed by the Coblenz fauna westward along the North Atlantic continent" (J. M. Clarke). In other words, there must have been a land connection between Europe and North America.

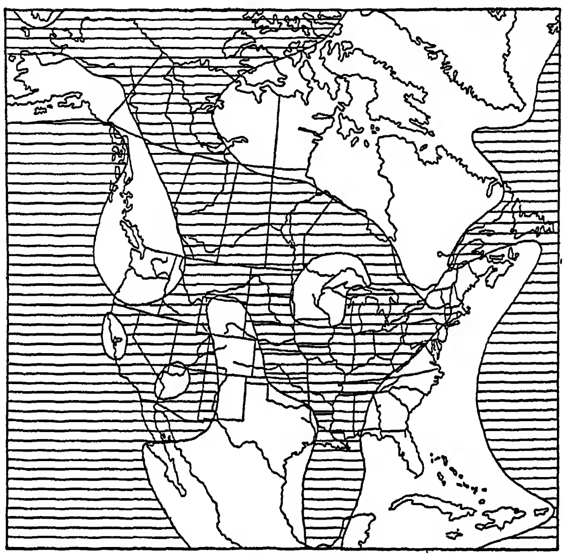


Fig 82

Paleogeographic map of North America during late Middle and Upper Devonian time. White areas, land, ruled areas, sea (Principal data, modified by the author, from maps by B. Willis and C. Schuchert.)

Middle Devonian.—An outstanding feature of North American Devonian history was the more or less steady advance of marine waters from the beginning of the period to beyond the middle. This marine invasion, first in the east and then in the west, reached a grand climax in late Middle Devonian (or Hamilton) time when fully 40 per cent of the continent was submerged as shown by map Fig. 82. This was one of the five or six greatest known floods in the

history of North America It should be noted that Appalachia and Canadia were connected across New England and the Upper St. Lawrence Basin

During early Middle Devonian (Onondagan) time in eastern North America, the sea must have been mostly clear, shallow, and comparatively warm as indicated by the widespread accumulation of coralline limestone. Evidently there were no rapidly eroding lands.

Late Middle Devonian (Hamilton) time witnessed an interesting physical change probably due to a very considerable rejuvenation of northern Appalachia, resulting in renewed erosion and deposition of vast quantities of muds in the eastern part of the interior sea. These muds are now hardened and called the Marcellus and Hamilton shales. Farther westward in the Mississippi Basin, however, much limestone still formed in the clearer sea.

Late Devonian. — The great sea which was so extensive in the late Middle Devonian continued to cover nearly the same areas in early Upper Devonian time. Then the sea began to retire from the land, first from the east and finally from the west, leaving the whole continent, as far as we know, dry land at the close of the period.

In New York and the northern Appalachian region, there was a tremendous accumulation of sandstone together with more or less shale and conglomerate. The Chemung-Catskill formation, as already stated, is largely a shallow-water, non-marine deposit from 1500 to 8000 feet thick in New York and Pennsylvania. The few known fossils are non-marine types. This, together with the common occurrence of red shales and sandstones, and the great thickness of the beds, all point to the origin of this remarkable formation as either a great delta deposit pushed out into the shallow interior sea, or as an estuarine or lagoon deposit. Notable thinning toward the west proves the material to have come from the east, doubtless from greatly rejuvenated Appalachia. Farther westward, over Michigan, Indiana, and Tennessee, the deposits formed at the same time were mostly shales, usually not over a few hundred feet thick.

Close of the Devonian (Acadian Revolution). — Because the late Devonian sea withdrew entirely from the continent, no transitional Devonian-Mississippian strata are known. In other words, the Devonian and Mississippian systems of rocks are separated by an unconformity, though usually not a profound one.

Fig. 83

Upper Devonian shales along the Genesee River in western New York. (Photo by C. Streb, courtesy of the New York State Museum.)

Real mountain-making is known to have taken place in only one region, namely, throughout most of New England, New Brunswick, Nova Scotia, and Newfoundland. This has been called the Acadian Revolution. The movement of folding and elevation, accompanied by igneous activity (both plutonic and volcanic), began well before the end of the period and reached a climax near its close. Succeeding Mississippian strata rest by unconformity upon the more or less upturned and eroded rocks of the region.

The rise of the Acadian Mountains no doubt so rejuvenated northern Appalachia that a large stream from it produced the great Late Devonian delta above described.

Foreign Devonian

Europe. — It may be said in general that the Devonian of Europe began with a progressive transgression of the sea, continuing till near the close of the period when much of the continent was submerged as shown in Fig. 84. The more or less well defined land barrier, which, since Cambrian time, had quite effectually kept Europe divided into two provinces or basins of deposition (a northern and a southern), still persisted

In the southern British Isles there are thick marine strata containing much contemporaneous igneous rock (lava sheets), while in the northern portion occurs the famous "Old Red Sandstone" which is largely of continental origin. This sandstone attains a greatest thickness of fully 20,000 feet, of which 6000 feet are interbedded lavas and tuffs. Deposition of the sandstone appears to have taken place, probably partly as delta and partly as wind-blown deposits, in basins or lagoons more or less cut off from the open sea, or at times in fresh-water lakes. Fossils are not abundant, but they constitute a remarkable assemblage of land, fresh water, and marine species scattered through various horizons. In many respects the "Old Red Sandstone" is much like the Chemung-Catskill formation of America.

The typical marine strata of Germany also contain many beds of lava, thus indicating much igneous activity during the period.

In west-central Europe much of the Devonian has been metamorphosed.

Typical marine limestones, shales, and sandstones were extensively deposited in Spain, France, Switzerland, much of Austria,

and Russia, but with Lower Devonian mostly absent from Russia. Coralline limestones are prominent in the Alps.

Other Continents. — The Devonian sea spread over most of Siberia and into central Asia and China. Rocks of this age are also known in various parts of southern Asia, northern and southern Africa, Australia, New Zealand, and in South America they

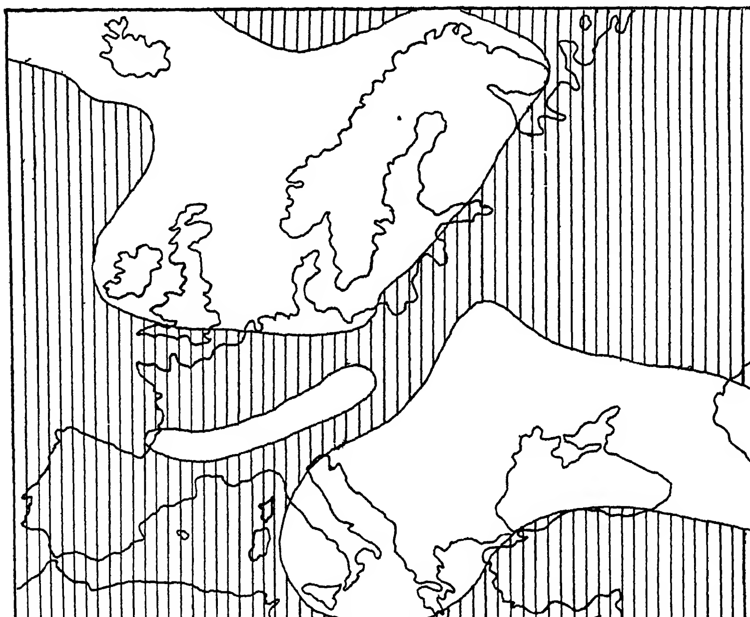


Fig 84

Sketch map showing the relations of land and water in Europe during the Upper Devonian. White areas, land; ruled areas, sea. (Modified by the author after F. X Schaffer)

appear to be more widespread than the rocks of any other Paleozoic system. Most of South America must have been submerged under a transgressing sea.

Climate

The general distribution and character of the fossils, as for example the Corals of the Onondaga sea, indicate rather mild and

uniform climatic conditions. Possibly such red formations as the Catskill and the "Old Red Sandstone" were formed under arid or semi-arid conditions. What appears to be boulder clay with striated pebbles, implies at least local glaciation in South Africa.

Fig 85

A restoration of one of the oldest trees of the earth It is a primitive Lycopod (*Archeosigillaria primeva*) reconstructed from a specimen found in the Devonian strata of New York. (Courtesy of the New York State Museum)

Economic Products

Oil and gas are principally derived from Devonian strata in the great fields of western Pennsylvania, West Virginia, and western New York.

Flagstones of Devonian age are extensively quarried in southern New York and in Pennsylvania.

Black phosphate deposits occur in the Upper Devonian shales of central Tennessee.

Life of the Devonian

Plants. — Of the *Algæ*, both Sea-weeds and Diatoms are known in fossil form, though they are not abundant. Certain forms regarded as tree-like *Sea-weeds* were remarkable for their size, having attained a diameter of two or three feet. *Diatoms* are unicellular, aquatic plants of microscopic size which secrete shells of silica, and some of Devonian age are known. In some of the later periods these tiny plants were of considerable importance.

No *Bryophytes* (Mosses) have yet been discovered. Spores and spore-cases of certain aquatic plants (Rhizocarps), probably related to very simple *Pteridophytes*, are very abundant in the black shales, especially those of Marcellus and Hamilton ages. According to Dawson they are "dispersed in countless millions of tons through the Devonian shales," and by their decomposition much oil has been produced.

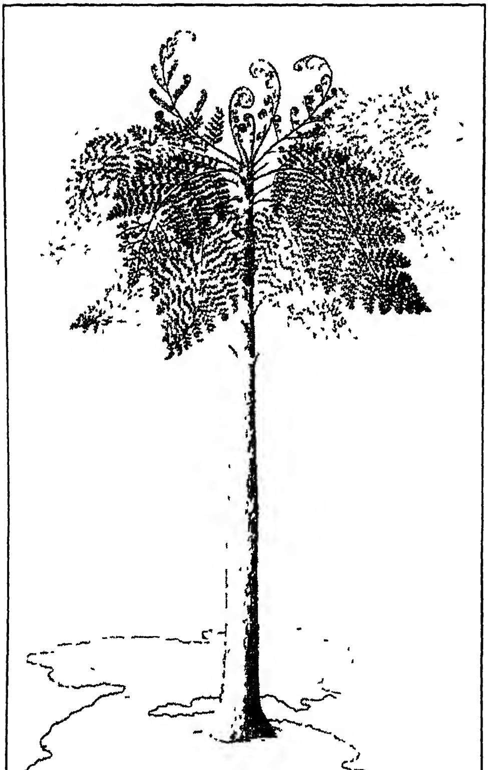


Fig 86

A restoration of a primitive treelike Seed-fern (*Eospermatopteris*) from the Devonian strata of New York. (Courtesy of the New York State Museum)

Our knowledge of land plants prior to the Devonian is very scant as we have seen, but the records are sufficient to make it certain that the Devonian lands were covered with a rich and diversified vegetation, often even with luxuriant forests. The forests were, however, far different in appearance from those of the present because the trees were all of very simple or low organization types. Figs. 85 and 86 represent two types of these very primitive trees. Thus they were largely represented by all the main subdivisions of the non-flowering *Pteridophytes* such as *Lycopods*, *Equisetæ*, *Ferns*, and *Seed-ferns*, and some simple types of the lower order of flowering

plants (i.e. *Gymnosperms*) were also present. Since these important and remarkable land plants reached their climax of development in the Pennsylvanian (great coal period), it will serve our purpose best to discuss these plants in connection with the flora of the Pennsylvanian.

Invertebrates. — Unless otherwise stated, the Invertebrate

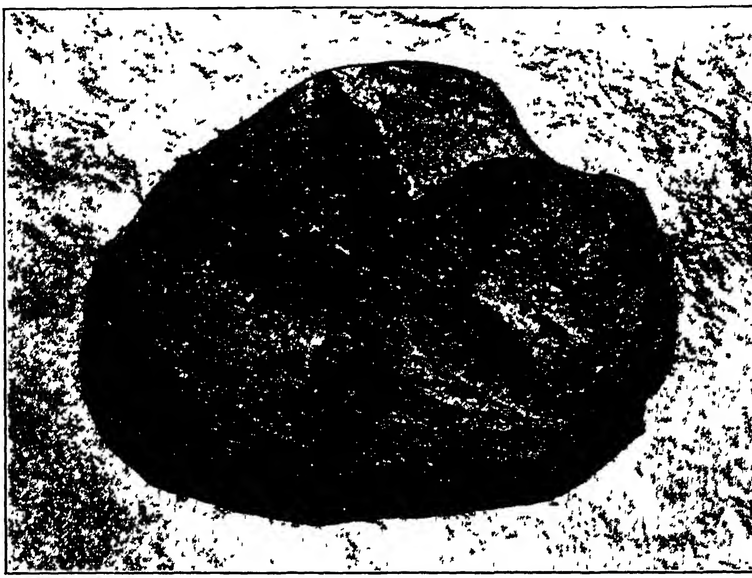


Fig 87

A Devonian Asterozoan, *Paleaster eucharis*, on a Pelecypod shell. (After Clarke, *N. Y State Mus Bul 158*)

animals were in general much like those of the Silurian. There were of course many changes in species, and even in genera, but in our elementary discussion, with emphasis only upon larger evolutionary features, it is our purpose to point out only a few of the more interesting changes among Devonian Invertebrates.

Sponges have been found in a remarkable state of preservation in the Devonian of New York. Certain of these, known as "glass Sponges," had siliceous skeletal frameworks of beautifully intricate designs (Fig. 92).

Corals displayed a very marked increase in numbers, species, and size. They must have grown in profusion, especially in the clear Onondaga sea, as proved by the many great fossil Coral reefs.

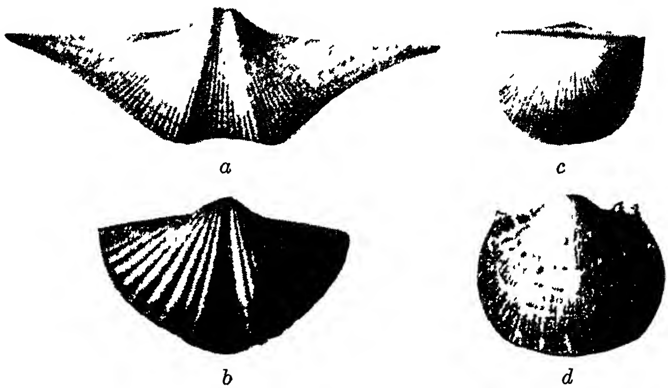


Fig 88

Devonian Brachiopods *a, Spirifer disjunctus, b, Spirifer intermedius; c, Stropheodonta demissa, d, Productus Hallanus* (All from Md Geol Survey, "Devonian")

From near Louisville, Kentucky, alone more than 200 species are known, and these are only a fraction of all described Devonian species. They were almost all of the cup and honeycomb types, the Chain Corals having become rare and extinct in the early Devonian. The solitary Cup Corals probably reached their culmination in size, some of them being 12 to 18 inches long and several inches in diameter.

Among the *Echinoderms* the *Cystoids* became extinct during the Devonian. *Bryozoans* were present, but not conspicuous as reef builders.

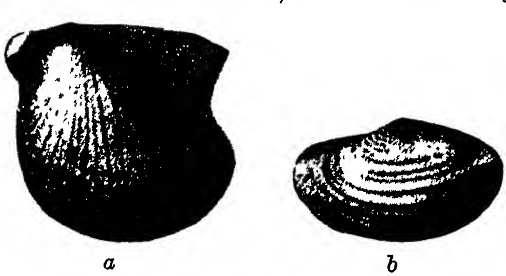
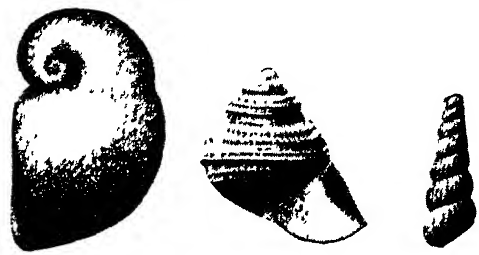


Fig. 89

Devonian Pelecypods: *a, Actinopteriate textilis, b, Grammysia arcuata* (From Md. Geol Survey, "Devonian")

Brachiopods reached their cul-

mination as regards numbers of species and abundance (Fig. 88). Here, as in the three preceding periods, Brachiopods were the most numerous fossils, and most of them still had straight hinge lines. Many Spirifers, particularly the wide "butterfly" genera (Fig. 88a), were common and characteristic. The genus Pentamerus was also represented by many forms.



a b c

Fig 90

Devonian Gastropods a, *Platyceras gebhardi*, b, *Pleuromaria capillaria*, c, *Loxonema hamiltoniæ* (From Md. Geol Survey, "Devonian ")

Among the chambered *Cephalopods*, a significant change took place with the introduction of the *Ammonoids* (e.g. *Goniatite*, Fig. 91) in which the septa or partition junctions were angular or irregular instead of simple or straight as in all previous forms (Nautiloids). As we shall see, this irregularity of partition structure gradually evolved into more and more complex forms, reaching a maximum in the Mesozoic era. (See table on page 114) Most of the common Nautiloid types still persisted, though the simpler forms (straight and slightly curved) were notably diminished in prominence.

Fig 91

A Devonian Goniatite, *Manticoceras patersoni* (After Hall)

Trilobites showed a marked decline in numbers and species, though they were not uncommon, and were still often fantastically decorated.

Arachnids were represented by *Spiders*, *Scorpions*, and *Eurypterids*, and the *Myriapods* made their first known appearance. *Eurypterids* probably culminated in the preceding period, but they were still prominent and notable for great size, one type having attained a length of eight feet. It is significant that the Scorpions, Spiders, and Myriapods were all air-breathers.

Fig 92

Restorations of Upper Devonian life of New York. Glass-sponges (at left), close-coiled chambered Cephalopod (at left middle), straight chambered Cephalopod (at right middle), stalked Echinoderm or "Stone-lily" (at right), Fishes, Asterozoans, and Pelecypods (Courtesy of the New York State Museum.)

Simplest Vertebrates. — Perhaps the most interesting and important feature of Devonian life was the profusion and development of the simple Vertebrates, particularly the *Fishes.* These simple or primitive Vertebrates are of unusual significance because they were the progenitors of the great groups of higher Vertebrates, which gradually became more complex and diversified, and finally culminated in Man himself. Nearly all known Devonian Vertebrates were aquatic.

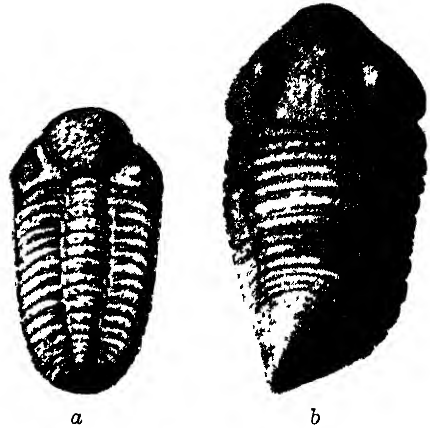


Fig. 93

Devonian Trilobites: *a*, *Phacops logani* (Hall); *b*, *Homalonotus noticus* (Clarke).

Paleospondylus.—This remarkable creature was an exceedingly simple and primitive type of Vertebrate. Its appearance is well shown in Fig. 94. The animal, one or two inches long, possessed a distinct, slender, segmented, cartilaginous vertebral column supplied at one end with a rather symmetrical tail fin structure, and at the other with a head. The head had a circular mouth but no jaws. Its lack of jaws and paired fins cause it to rank below the true Fishes, and it is probably to be classed with the Lamprey Eels.

Fig 94

A very simple Devonian Vertebrate, *Paleospondylus gunni* (After Dean, restored by Traquair, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company)

Ostracoderms. — These curious and bizarre forms also represent a very simple class of the Vertebrates. For a long time they were classed as simple Fishes, but recent study has led some to believe that they are really transition forms between the highest invertebrates (Arthropods) and the Fishes which rank very low among the Vertebrates.

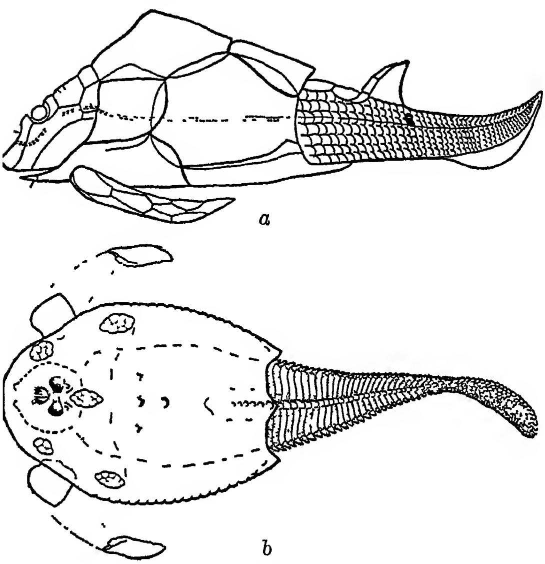


Fig 95

Devonian Ostracoderms *a*, *Pterichthys testudinarius*, restored (Dean after Woodward), *b*, *Tremataspis*, restored (after Patten)

A characteristic feature is the cover or armor of bony plates developed in the skin over the head and fore part of the body, hence the name, which literally means "shell-skin." The rear part of the body was generally covered with scales. Some had vertebrated tail fins and were fish-like in appearance (Fig. 95a). They were rarely if ever more than 6 or 8 inches long. Some had a pair of jointed flappers or swimming paddles extending out from the fore part of the body, but none had true paired fins like the Fishes. The vertebral column was of cartilage (gristle). The eyes were close together near the top of the head. They did not possess true jaws in the Vertebrate sense of that term, but rather the simple jaw-like portions moved over each other laterally as in many Arthropods (e g. Beetles).

Ostracoderms reached the zenith of their development in the Devonian, and, so far as known, they became extinct during the same period.

Fishes. — Because of the profusion of Fishes, the Devonian is

often called the "Age of Fishes." Their abundance, together with their importance as bearing upon the evolution of the Verte-

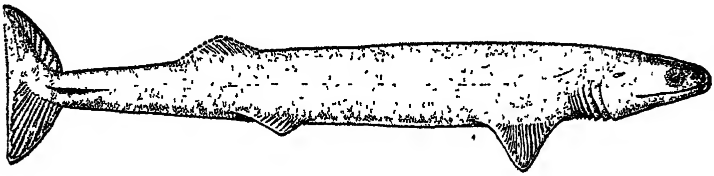


Fig 96

A Paleozoic (early Mississippian) Selachian or Shark, *Cladoselache fyleri* (Restored by Dean)

brates, requires that considerable attention be devoted to the Fishes here. In all of our discussion of the geological history of Fishes, the following important groups only will be recognized: (1) *Selachians* ("Cartilage" - fishes), now uncommon, but e.g. Sharks, (2) *Dipnoans* ("lung"-fishes), now rare, but e.g. Ceratodus of Australian rivers; (3) *Arthrodirans* (e.g. Fig. 97b), now wholly extinct; (4) *Ganoids* ("lustre"-fishes), now uncommon, but e.g. Gar-pike and Sturgeon; and (5) *Teleosts* ("perfect bone"-fishes), now the most abundant of all Fishes, e.g. Trout, Salmon, Cod.

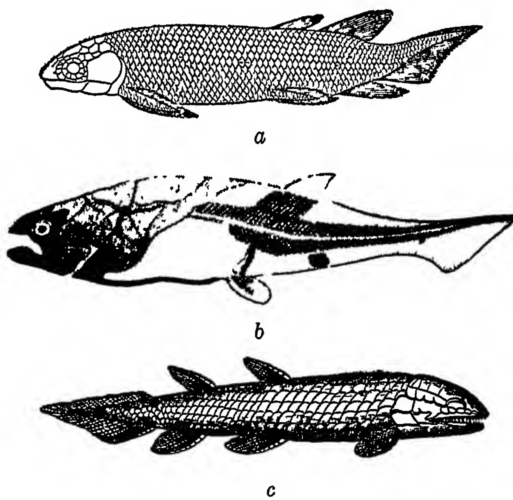


Fig 97

Devonian Fishes: *a*, Dipnoan, *Dipterus valenciennesi* (restored by Traquair); *b*, Arthrodiran, *Coccosteus decipiens* (restored by Woodward); *c*, Ganoid, *Osteolepis* (restored by Nicholson)

Selachians are the simplest of all true Fishes, and they comprise

the oldest group of living Fishes, dating back at least to the Silurian. Their skeletons are wholly cartilaginous, the only hard parts being the teeth and fin spines which are commonly preserved as fossils. The arrangement of separate gill slits in the throat wall is a more eel-like than fish-like feature. Simple, paired fins are present, but scales or plates are absent. They were common in the Devonian seas, and also probably in lakes and lagoons. Fig. 96 exhibits a typical Paleozoic species which is very similar to living forms.

Dipnoans are remarkable in being able to breathe both in water and air, since they have both gills and lung, the air-bladder being more or less used as a lung. They were abundant during Devonian time. Fig. 97a shows a common Devonian species which is remarkably similar to the modern Ceratodus. Note the paddle-shaped paired fins, almost like legs, and the covering of scales. Their skeletons were cartilaginous. Their limb-like fins and peculiar lung-like air sacs were more amphibian-like than fish-like characters and they strongly suggest that the Dipnoans may have been the progenitors of the Amphibians.

Arthrodirans comprise a remarkable group of Fishes now wholly extinct, but they were common in Devonian time Fig. 97b shows an example of a well-known genus (Coccosteus) from the Old Red Sandstone. Note the bony armor covering the fore part of the body, thus suggesting the Ostracoderms, though the paired fins and true jaws supplied with teeth place them with the Fishes. The backbone was of unsegmented cartilage. Other forms closely related to Coccosteus were remarkable for size, some having attained lengths up to 20 or 25 feet. Arthrodirans were probably the most formidable denizens of the Devonian seas

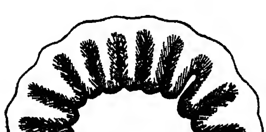


Fig. 98
Structure of a Ganoid tooth
(After Agassiz)

Ganoids were the most highly organized and abundant Fishes of the time. These were characterized by a covering of small lustrous plates or bony scales, usually rhomboid and set together like tile, rather than by overlapping as in typical modern Fishes. The skeletons were of cartilage, though in later periods they were more or less ossified as in the few modern representatives. Their internal tooth structure was often labyrinthine (Fig. 98) or much like that of

Amphibians of later Paleozoic periods. A typical Devonian Ganoid is shown in Fig 97c. The so-called fringe-finned Ganoids were externally rather similar to the Dipnoans, especially as regards the paired, lobate, limb-like fins. Their intricate (labyrinthine) tooth structure, character of the skull bones, and limb-like fins, suggest strong affinities with the Amphibians of the later Paleozoic.

Teleosts, which are the most common and typical modern Fishes, were entirely absent from the Devonian. In these the skeletons are completely ossified and the body is nearly always covered with overlapping scales. In marked contrast with the Devonian Fishes, Teleosts always have non-vertebrated tail fins.

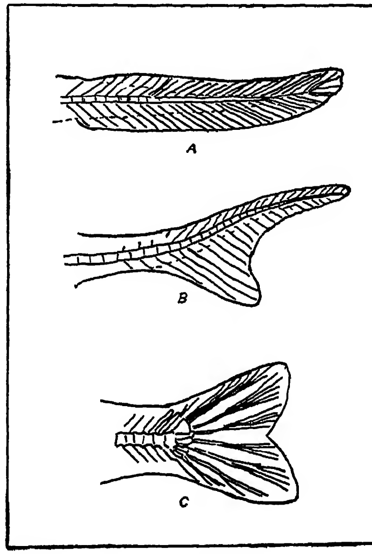


Fig 99

Types of Fish tails: *a,* vertebrated symmetric; *b,* vertebrated non-symmetric; *c,* non-vertebrated symmetric (Redrawn after Le Conte.)

General Observations on Devonian Fishes. — (1) All were of simple types. The most typical and highly organized Fishes so common today, did not exist in the Devonian, and even the Ganoids were of primitive types.

(2) All had cartilaginous skeletons The vertebral column and other portions of the skeleton were not ossified (i e. changed to bone).

(3) All had vertebrated tail fins. The vertebral column extended through the tail fin and gave off fin rays to support a lobe above and below. Sometimes this tail fin was symmetric and sometimes asymmetric. The asymmetric form is regarded as the more primitive. Most modern Fishes (Teleosts) have non-vertebrated tail fins, the fin rays being sent out from a plate at the end of the vertebral column.

(4) They were generalized types. "Along with their distinctive fish-characters, they combined others which connect them with higher Vertebrates, especially Amphibians, and still

others which are found in the embryos of Teleosts. The most important connecting characters . are. (a) An external protective armor of thick bony plates or scales such as were possessed by early Amphibians, and by many Reptiles of the present time, (b) Large conical teeth channelled at the base, and of labyrinthine structure on section. This structure was very marked in early Amphibians, (c) A cellular air-bladder . . . capable of being used to some extent as a lung; (d) In many cases paired fins which had something like jointed legs running through them; (e) The tail fin vertebrated as in Reptiles."[1] The most prominent embryonic characters were the cartilaginous skeleton found only in the embryonic stage of the typical modern Fishes (Teleosts), and the vertebrated character of the tail fin, the tail of the modern Teleost successively passing from the asymmetric vertebrated stage, to symmetric vertebrated, and finally to symmetric non-vertebrated (Fig. 99).

Generalized or synthetic types, so well illustrated by Devonian Fishes, are of great importance in considering the evolution and geological history of organisms

Amphibians. — Footprints, considered to be those of Amphibians, have been found in the Upper Devonian strata of Pennsylvania, but remains or impressions of the animals are not known. At any rate it seems certain that terrestrial Vertebrates existed as early as the Devonian, and thus a new, important advance in the evolution of life had taken place.

[1] J. Le Conte. *Elements of Geology*, p 356.

CHAPTER X

THE MISSISSIPPIAN (LOWER CARBONIFEROUS) PERIOD

Origin of Name, Subdivisions, Etc.

Formerly the Carboniferous period included all of what, in America at least, we now call the Mississippian, Pennsylvanian, and Permian periods.[1] In Europe the term Carboniferous is still employed, though the Permian has been separated from it. The name "Carboniferous" was given about one hundred years ago because it was supposed that workable coal beds were almost, if not wholly, confined to that system. Although workable coal beds are known to occur in most later systems, nevertheless what was long known as Carboniferous, particularly that portion now called Pennsylvanian, does contain the world's greatest coal deposits. The name "Mississippian" was given because of important outcrops of its formations in the eastern Mississippi Basin, especially along the river.

Some idea of the system in three well-known regions may be gained from the following table:

	Mississippi River States	*Pennsylvania*	*Idaho and Utah*
Upper Mississippian	4 Chester or Kaskaskia series (Limestones, sandstones and shales). 3. St Louis or Iowan series (Limestones).	2 Mauch Chunk (Shales).	2 Brazer (Limestone).
Lower Mississippian	2. Osage or Augusta series (Limestones and shales) 1. Kinderhook or Chattanooga series (Limestones, shales, and sandstones)	1. Pocono (Sandstone)	1. Madison (Limestone).

[1] In its geologic folios the U. S. G. S. still uses the term Carboniferous.

It will be seen that, in the Appalachian region, the rocks are almost wholly clastic, while limestones are prominent in the Mississippi River region. Also the system in the east has not been so much subdivided, and detailed correlations with the subdivisions farther west have not been made. Regarding the detailed classification of subdivisions in America, much difference of opinion still exists, and more or less local names are used in different regions.

Distribution and Character of the Rocks

General Distribution. — The accompanying map (Fig. 100) shows the surface distribution of the Mississippian and Pennsylvanian rocks together. In the western part of the continent these two systems usually have not been satisfactorily separated, hence it is impossible to delimit them separately upon the map Also it must be borne in mind that the large areas in British Columbia and Alaska contain considerable amounts of other Paleozoic rock as well as early Mesozoic rock, though the Mississippian and Pennsylvanian are abundantly represented. In the eastern part of the continent, the two systems have been clearly separated, and map Fig 101 shows the surface distribution of Mississippian strata there. A comparison with the Devonian surface distribution map (Fig. 80) shows that the Mississippian has a very similar distribution in eastern North America, and that the Mississippian generally borders the Devonian areas This is because Devonian conditions gave way to Mississippian with no great interruption of deposition. A distribution feature of special importance as compared with the Ordovician and Silurian, and to some extent with the Devonian, is the complete absence of Mississippian strata from all of northern North America east of the Rocky Mountains except around the mouth of the St Lawrence River.

In the Appalachians, Rockies, and mountains still farther west, the outcropping strata form long and short, narrow belts because the rocks have been highly folded and only the eroded edges of upturned strata are visible (Fig. 132). The eastern Mississippi Basin shows a different type of distribution because the rocks are there in nearly horizontal position and outcrop where the later (overlying) Paleozoic strata have been removed from them by erosion, or where later sediments were never deposited upon them. The character of the rocks and distribution of outcrops, supple-

mented by many deep well sections, proves that Mississippian strata underlie nearly the whole Mississippi Basin except the Gulf border, and Wisconsin and Minnesota.

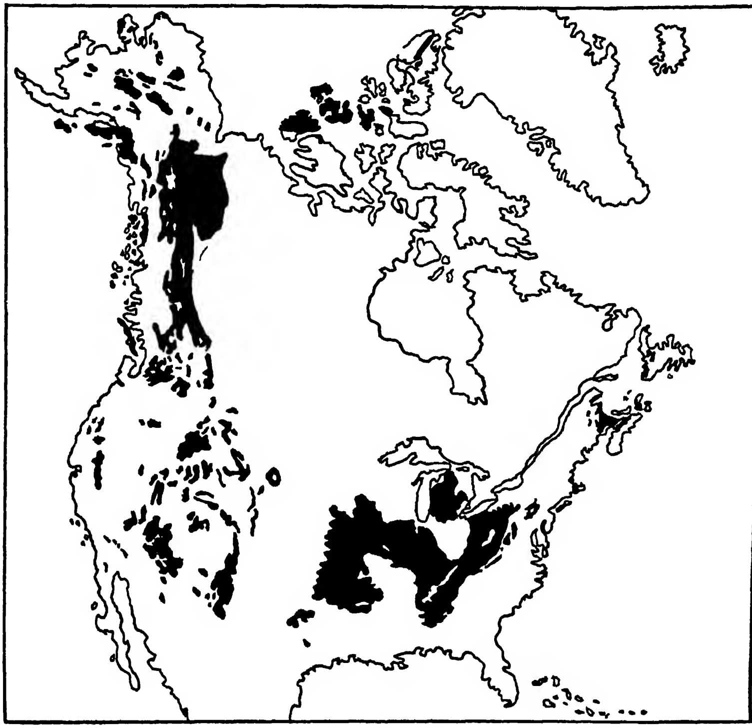


Fig 100

Map showing the surface distribution (areas of outcrops) of Mississippian and Pennsylvanian strata in North America The areas in British Columbia include some other Paleozoic rocks as well as some early Mesozoic rocks (By W. J M , data from Willis, U. S Geological Survey)

Lower Mississippian Rocks in the East. — The *Pocono* sandstone, also including some conglomerate, shale, and thin beds of coal, extends from northern Pennsylvania to Virginia in the Appalachian district. Its thickness varies from about 2000 feet in Pennsylvania to about 100 feet in the south. As judged by numerous terrestrial fossils, the Pocono appears not to be a typical marine

deposit. Just west of the Appalachians considerable shale is associated with the sandstone of this same age, while in the Mississippi River states the Lower Mississippian is represented by the *Kinderhook* and *Osage* series, which contain much limestone. The Kinderhook consists of sandstone, shale, and limestone, but

Fig 101

Map showing the surface distribution (areas of outcrops) of Mississippian strata in eastern North America. (Modified by W. J M. after Willis, U. S. Geological Survey)

varies greatly in lithologic character from place to place. The Osage series directly overlies the Kinderhook, and is dominantly limestone, though with some shale. Both Kinderhook and Osage are chiefly true marine deposits. Lower Mississippian strata in southern Michigan are mostly sandstones and shales (often red), with some interbedded salt and gypsum deposits.

Upper Mississippian Rocks in the East. — In the northern Appalachian district, the *Mauch Chunk* formation, consisting mostly of red sandy shales, directly overlies the Pocono, while in Maryland and West Virginia the lower portion of the Mauch Chunk gives way to the *Greenbrier* limestone. The Mauch Chunk shows a maximum thickness of 3000 feet in eastern Pennsylvania, but this diminishes notably to the north, west, and south. It is considered to be either a great flood-plain or a delta deposit. Farther west, in the Mississippi River states, the Upper Mississippian is represented by the *St. Louis* and *Chester* series. The former is made up almost wholly of limestone of very widespread extent, while the latter is rather variable lithologically, and is more restricted in distribution.

The Mississippian of Nova Scotia and New Brunswick has not been so carefully subdivided, but it is largely sandstone below and limestone, with some red beds and gypsum, above. Its thickness reaches a maximum of about 5000 feet.

Mississippian of the West. — This system is very widely distributed in the west as proved by the numerous exposures, but it has not been carefully studied and subdivided as in the east. Throughout the system, which is commonly several thousand feet thick, limestone greatly predominates. A very widespread formation in the Rocky Mountains is the *Madison* limestone which reaches a thickness of 1600 feet.

Thickness of the Mississippian. — The Mississippian system in eastern North America ranges in thickness from about 5000 feet in eastern Pennsylvania to only some hundreds of feet in the western part of the same state. In the Mississippi River states the maximum thickness is 1500 feet, though it is generally less than 1000 feet. In the western part of the continent thicknesses of several thousand feet (maximum over 4000 feet) have been observed at several places, while in other localities, as in the Black Hills and parts of Colorado, it measures only a few hundred feet thick. Eighteen hundred feet are known in the Grand Canyon of the Colorado River. In Nova Scotia and New Brunswick the thickness of the Mississippian strata reaches fully 5000 feet.

Igneous Rocks. — There is but little evidence of Mississippian igneous activity in North America. Sheets of igneous rocks are associated with Mississippian strata in Nova Scotia and New Brunswick.

Physical History

Earlier (Lower) Mississippian. — The continent was all, or nearly all, land at the opening of the Mississippian period. Disregarding certain minor shiftings of the sea, the great event of Early (Lower) Mississippian time was an increasing expansion of the sea over the land until late Lower Mississippian (Osage) time when about one-third of the continent was submerged.

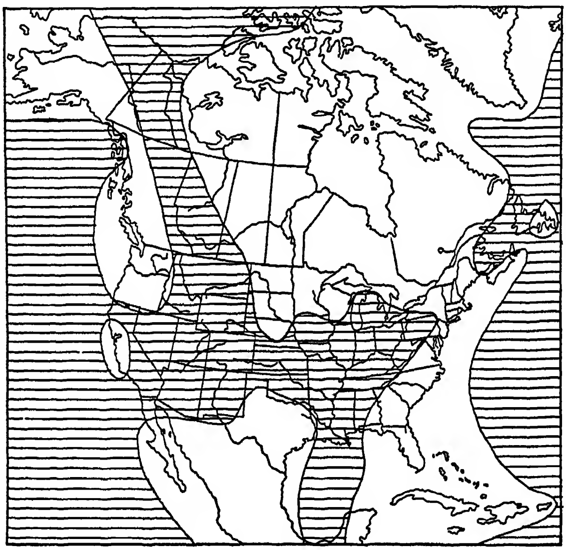


Fig 102

Paleogeographic map of North America during late Lower Mississippian time White areas, land, ruled areas, sea (Principal data, modified by the author, from maps by B. Willis and C. Schuchert)

Fig. 102 shows the general relations of land and water of that time. Much of the area of the United States was covered by an unbroken expanse of shallow-sea water with wide connections with the Pacific and Arctic Oceans and the Gulf of Mexico. Canadia was very large and connected with Appalachia across New England. Cascadia and Mexicoia were well-defined as such.

During Lower Mississippian time coarse clastic sediment (Po-

cono sandstone) was deposited along the western shore of Appalachia; red beds, with interbedded salt and gypsum, formed in lagoons bordering southern Canada; at first muds (Chattanooga), and then highly fossiliferous limestone (Kinderhook and Osage), accumulated in the great sea of the Mississippi Valley area; while the widespread, thick Madison limestone accumulated in the Rocky Mountain region

In the midst of the period, that is between Lower and Upper Mississippian times, there was a very considerable withdrawal of the sea, moderate in the east, but almost complete in the Rocky Mountain region.

Later (Upper) Mississippian. — During Upper Mississippian time there was a tendency for the waters again to spread over the late Lower Mississippian areas, but not so extensively. Thus the middle and middle-northern parts of the United States were not submerged, and the sea was more restricted over the site of the Rocky Mountains, extending over the northern portion of the latter region only in the Late Mississippian if at all.

In the east, during later Mississippian time, vast quantities of clastic sediments continued to deposit as muds (now Mauch Chunk shales) above the Pocono sands along the western shore of Appalachia. Locally conditions were right for coal formation as proved by some coal beds in the Mauch Chunk. The interior sea, however, had clearer waters in which limestone deposition greatly prevailed. This clear sea extended westward across the United States to the Pacific Ocean. More red beds with associated salt and gypsum continued to form in southern Michigan lagoons. Also red beds and gypsum were formed in Nova Scotia.

Close of the Mississippian (Ouachita Revolution). — The complete emergence of the continent at the close of the Mississippian was brought about largely without folding or tilting of the strata. In certain regions, however, there were actual mountain-making movements, though not on a large scale. Thus, a nearly east-west zone through Arkansas and Oklahoma, where a thick body of strata had accumulated during five periods of the Paleozoic, was subjected to pressure, considerably folded, and uplifted into mountains. This involved the Ouachita and Wichita Mountains of Arkansas and Oklahoma, and hence has been called the Ouachita Revolution.

Mississippian and older rocks in parts of Nova Scotia and

New Brunswick were also notably folded and elevated as proved by the fact that Pennsylvanian strata there rest upon upturned, eroded edges of Mississippian and older rocks. The newly exposed lands of the continent were notably eroded, and the Mississippian and Pennsylvanian systems are separated by one of the most extensive and distinct unconformities in the whole Paleozoic group of rocks For this reason the Mississippian and Pennsylvanian should be regarded as separate systems rather than as merely subdivisions of the old Carboniferous.

Comparisons with Preceding Systems. — The comparison of the Ordovician, Silurian, and Devonian systems given in the preceding

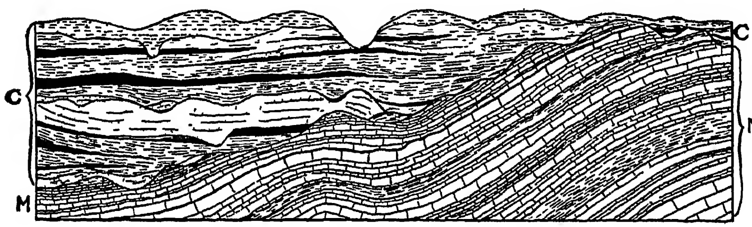


Fig. 103

Generalized section in Iowa, showing how the Pennsylvanian system (*C*) rests unconformably upon the Mississippian (*M*). (After Keyes, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company)

chapter (page 139) to show a certain rhythmic recurrence of events might also fairly include the Mississippian, because this period, like the others, began with a sea transgression which reached a maximum (accompanied by much limestone making) about the middle of the period, followed by widespread withdrawal and shoaling of the sea, and deposition of clastic sediments toward the close of the period.

Foreign (Lower Carboniferous) Mississippian [1]

Europe. — As in North America, there was considerable encroachment of the sea so that much of the non-marine Old Red Sandstone became covered with true marine sediments. Map

[1] It should be remembered that the term "Mississippian" is not used in Europe.

Fig. 104 gives a general idea of the relations of land and water in Europe in Mississippian time. In western Europe limestone predominates. Marine waters, mostly free from land-derived sediments, extended from the western British Isles to central Germany. In these waters there lived vast numbers of organisms such as Crinoids, Corals, etc., the remains of which accumulated to build a great mass of limestone said to attain a thickness of

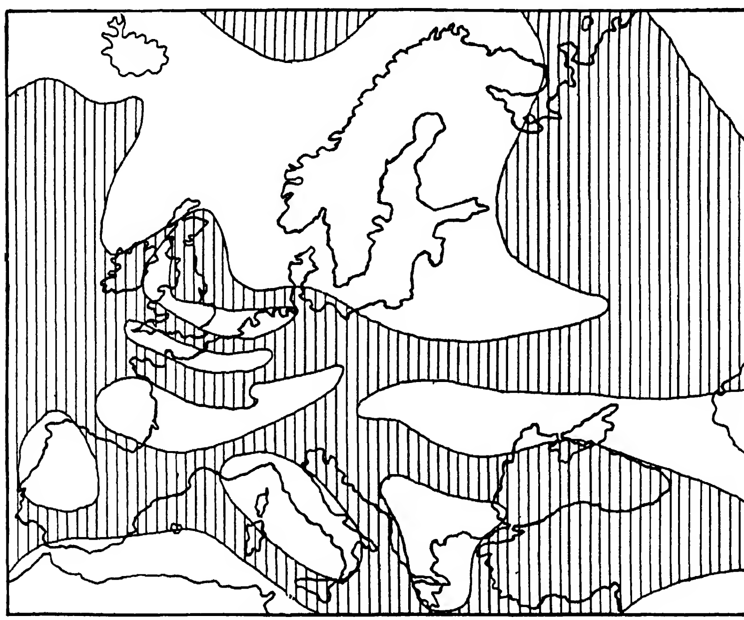


Fig. 104

Sketch map showing the general areas of submergence in Europe during Mississippian (Lower Carboniferous) time White areas, land; ruled areas, sea. (Modified by the author after De Lapparent)

6000 feet in England, and over 2000 feet in Belgium. Farther eastward, in central Europe, shales and sandstones were laid down. In Scotland and southern England also shallow water deposits were formed. Throughout much of central, southern, and eastern Russia, chiefly non-marine materials were deposited as proved by the many coal beds and associated deposits. The rocks of Missis-

sippian age in southern Europe are much like those of central Europe, and also the similarity of fossils shows that northern and southern Europe were not separate provinces as during most of earlier Paleozoic time.

Rather widespread crustal disturbances marked the close of the period in western Europe. As a result of the upturning and folding of the rocks, great mountains were formed principally as two chains — one extending from Ireland to central Germany, and the other from Bohemia to southern France. The structure of the remnants of these mountains, as seen in the Vosges, Harz, Black Forest, and Cornwall hills or low mountains, implies deformation intense enough to have produced high altitudes. Accompanying this deformation there were abundant intrusions and extrusions of igneous rocks. In many other parts of Europe there were relative changes of level between land and sea without very appreciable folding or tilting of the strata. Thus, the reason for separating the old Carboniferous into two systems applies with great force to Europe as well as to North America.

Other Countries. — In South America Mississippian rocks are known in Argentina where they contain some coal, in Chile, and in other parts of the continent where they have not been carefully separated from the Pennsylvanian (Upper Carboniferous).

Eastern Australia, New Zealand, and Tasmania contain marine strata of Mississippian age which were generally highly deformed toward the close of the period, and injected with igneous rocks. Salt and gypsum occur in the system in western Australia.

In northern Africa the system is extensively represented, especially by limestone. Non-marine formations occur in southern Africa.

Rocks of Mississippian age are also known to be widely developed in Asia.

Climate

As for the earlier Paleozoic periods, the character and distribution of Mississippian fossils rather clearly prove absence of climatic zones like those of today. A mild, uniform climate appears to have prevailed. Salt and gypsum beds more or less associated with red beds point to arid climate in Michigan, Montana, Nova Scotia, and Australia, but these were probably

local conditions. Evidence of glaciation toward the close of the period has been reported from Oklahoma.

Economic Products

Much oil is obtained from Mississippian sandstones in western Pennsylvania, West Virginia, Illinois, and Oklahoma.

Some gas is obtained from the Chester sandstone of Illinois, and some coal from the Pocono sandstone of West Virginia

Building stones of Mississippian age are considerably quarried, especially the oolitic Bedford limestone of Indiana, which is perhaps the most widely used limestone for building stone in the United States.

Vast quantities of salt are produced by pumping out and evaporating the natural brines from the Mississippian sandstones of Michigan, and smaller quantities from the sandstones, or limestones of Ohio, West Virginia, and Virginia.

Certain important zinc ore deposits occur in the Lower Mississippian limestones of Missouri and Kansas though the deposition of the ore was post-Mississippian.

Life of the Mississippian

Plants. — In general the flora of the Mississippian may be said to have been very much like that of the Devonian, though the former showed greater diversity and various minor changes. The records of land plants are perhaps not as full as those of the preceding period. Fossil plants are most numerous in early Mississippian rocks.

The simplest plants, such as *Thallophytes* and *Bryophytes(?)*, were present but their fossil forms are not known to be common.

The flora of the period consists almost entirely of the highest *Cryptogams* (i.e. *Pteridophytes*) and the simpler *Phanerogams* (i e. *Gymnosperms*). As in the Devonian, all the principal groups of the Pteridophytes — *Lycopods, Equisetæ* and *Ferns* — as well as the still higher *Seed-ferns* and simpler types of *Gymnosperms* were represented. All of these plant types are of unusual interest and importance but, because of their vastly greater abundance and better state of preservation in the Pennsylvanian rocks, it will be best to postpone their somewhat detailed discussion to the next chapter.

Invertebrates. — Unless otherwise stated the Mississippian Invertebrates were in general much like those of the Devonian or Silurian.

Foraminifers were exceedingly abundant, especially in the Middle Mississippian (St. Louis) sea. The famous Bedford limestone of Indiana, for example, is very largely made up of the tiny calcareous shells of these Protozoans. *Radiolarian* (siliceous)

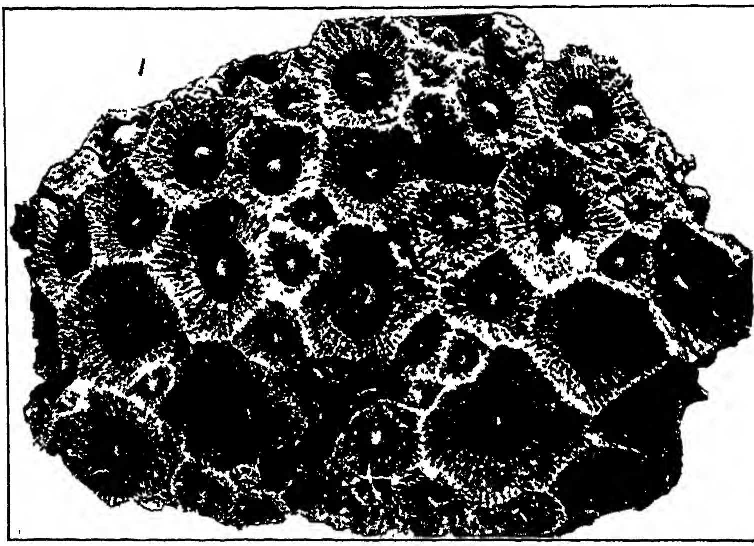


Fig. 105

Mississippian Cup-corals, *Lithostrotion canadense*, forming a compact mass or colony (After Ulrich, U. S Geological Survey, Folio 95)

shells are very abundant in some formations where they make up layers of chert.

Graptolites were very rare and became extinct. *Corals* showed a notable decline as compared with their remarkable development in the Devonian, though Cup-corals especially were locally numerous in the Mississippian seas (Fig. 105).

Blastoids, which, during several preceding periods, assumed a minor rôle, showed a wonderful development in the Mississippian when they appear to have reached their culmination both as regards

numbers of individuals and diversity of forms. (Fig. 106 shows one of the most common types, known as Pentremites, which largely constitutes beds of limestone in some places. At certain localities even the most delicate of the hard parts of the organisms are nearly perfectly preserved. It is a remarkable fact that this class of animals, which attained such prominence during this period, also became nearly extinct by the close of the same period.

Fig. 106

A Mississippian Blastoid head, *Pentremites elongatus* (After Shumard)

Crinoids also culminated during this period. Hundreds of species are known, and some localities such as Crawfordsville, Indiana, and Burlington, Iowa, are well known for the remarkable preservation of vast numbers of these beautiful forms (fossil "sea-lilies"). "The Crinoid remains occur in such multitudes that in many places the limestones are principally composed of them; in such places they must have covered the sea-bottom like miniature forests" (W. B. Scott). It is noteworthy that all of this wealth of forms belonged to a single subclass or order of Crinoids (Fig. 107), not one of which is known to have lived on into the Mesozoic. "The rapid decline (of Crinoids) after this epoch (Osage) is one of the most remarkable incidents in the life-history of the invertebrates. . . . The ornamentation of the Crinoids at this time was notable, and as in the case of the Trilobites, preceded the decline of the group. The repetition of this singular phenomenon at different times, and in quite different groups of organisms, is worthy of notice, though its meaning is not altogether clear." [1]

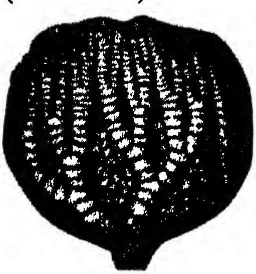


Fig 107

A Mississippian Crinoid head, *Forbesiocrinus wortheni* (After Hall.)

Bryozoans, in marked contrast with the Devonian, were very abundant, and in some cases the calcareous skeletons of the colonies contributed much material to the building of limestone. For the first time the delicate moss-like colony supports were partly replaced by thicker and heavier supports, a good example being

[1] Chamberlin and Salisbury: *College Geology*, pp. 607–609.

called *Archimedes* because of some resemblance to the familiar screw of the same name.

Brachiopods in general diminished notably, though they were by no means uncommon. Certain important earlier Paleozoic genera (e.g. *Pentamerus*) were entirely gone. The important genus *Spirifer* greatly diminished in numbers and size of indi-

Fig. 108

Mississippian Crinoids, *Graphiocrinus longicirrifer* and *Rhodocrinus Kirbyi*, on a slab of limestone Considerably reduced From Kinderhook formation, Le Grand, Iowa (Courtesy of the University of Chicago)

viduals. Perhaps the most important Mississippian genus was *Productus* with many species and some of the largest known individual Brachiopods. Straight-hinge line types still prevailed.

A very fine illustration of the production of a dwarfed fauna due to unfavorable environmental influences is afforded by the diminutive Brachiopods and associated shells of the Bedford limestone of Indiana. Since the species of these dwarfed forms are the same

as those which grew to normal size elsewhere, it is evident that they must have lived in an unfavorable environment.

Pelecypods were more common than ever before, and for the first time they appear to have been more numerous than the Brachiopods.

Cephalopods were much like those of the Devonian. All common groups of *Nautiloids* persisted but with the simpler forms still more diminished. The coiled forms, however, probably reached their climax of development both as regards numbers and diversity of forms. The *Ammonoids* were still represented by the *Goniatites*, though the sutures were appreciably more complex in accordance with the evolutionary principle already given in connection with this group.

Among *Crustaceans*, the *Trilobites*, which were approaching the period of their extinction, were few in number, comparatively small, and usually not highly decorated.

Among *Arachnids*, the remarkable group of *Eurypterids* had notably fallen off both in numbers and size as compared with the Devonian.

Vertebrates. — *Fishes.* — The *Selachians* (Sharks), as compared with the Devonian, showed an extraordinary development in numbers and species. They were doubtless the most prominent of all Fishes of the time, many hundreds of species being known. Teeth and spines are the most numerous fossils. In sharp contrast with most modern forms, many species had the mouths lined or paved with rough plate-like teeth probably suitable for grinding such shelled animals as Brachiopods, Pelecypods, etc. The spines were doubtless provided for defence against more predaceous Fishes. *Dipnoans* and *Arthrodirans* still continued though notably diminished. *Ganoids* were still prominent, probably having been more abundant than in the Devonian, with many new genera and species.

Amphibians. — As we have learned, there is good reason to think that Amphibians lived in Devonian time, though actual remains are not known. In the Mississippian rocks of Scotland good specimens of Amphibians have been found. Many footprints of Amphibians have been found in Upper Mississippian strata of Pennsylvania. These all belong to the long extinct and remarkable group of *Stegocephalians* which will be described in the next chapter because of their much more satisfactory preservation in the Penn-

sylvanian rocks. As already suggested in our discussion of Devonian Fishes, it is well-nigh certain that the earliest Amphibians were derived from a special kind of Fishes (Dipnoans). In fact the larval forms of Amphibians are true water animals breathing through gills and swimming like Fishes.

CHAPTER XI

THE PENNSYLVANIAN (UPPER CARBONIFEROUS) PERIOD

ORIGIN OF NAME, SUBDIVISIONS, ETC.

As stated in the preceding chapter, the Pennsylvanian system represents a part of what was formerly known as the Carboniferous system in America. In other continents, strata equivalent to the Pennsylvanian are usually called Upper Carboniferous Rocks of Pennsylvanian age include the Coal Measures proper of the old Carboniferous, and they contain a far greater supply of workable coal than the rocks of any other system. The name has been given because of the typical development of the system with its coal in Pennsylvania. Subdivisions in widely separated areas are shown in the following table·

	Eastern United States	*Central Texas*	*S. E Idaho*
PENNSYLVANIAN SYSTEM	4 Monongahela series (Various strata with much coal). 3. Conemaugh series (Various strata with little coal) 2. Allegheny series (Various strata with much coal) 1. Pottsville series (Various strata with some coal).	5 Cisco (Shale and sandstone). 4 Canyon (Limestone, sandstone, and coal) 3 Strawn (Sandstone, shale, and coal). 2. Southwick (Shale and sandstone). 1. Marble Falls (Limestone).	Wells (Limestone).

DISTRIBUTION AND CHARACTER OF THE ROCKS

General Distribution. — Only in the eastern part of the continent have the Mississippian and Pennsylvanian rocks been satisfactorily separated. The accompanying map (Fig. 109) shows the surface distribution of the Pennsylvanian in eastern

North America Two points of difference as compared with the older systems in this portion of the continent are worthy of mention as follows: (1) The Pennsylvanian rocks occupy distinctly larger (surface) areas of the Mississippi Valley-Appalachian region than the rocks of any older Paleozoic system, and (2) "the common-

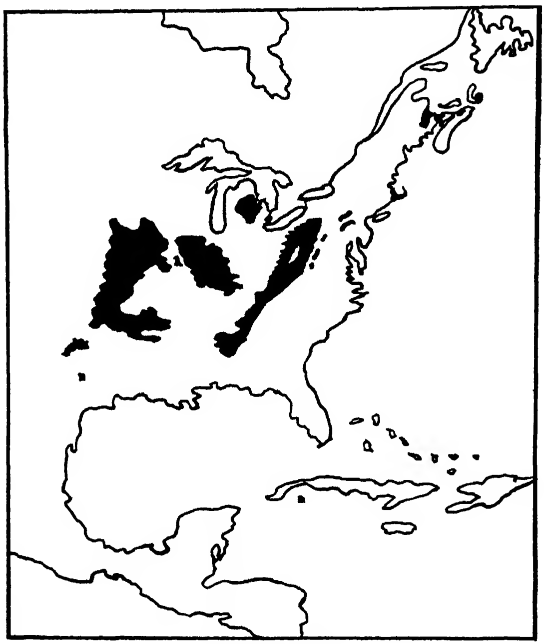


Fig 109

Map showing the surface distribution (areas of outcrops) of Pennsylvanian rocks in eastern North America. These are also essentially the great areas of Pennsylvanian coal (By W J M, data after Willis, U. S. Geological Survey)

est position for the outcrops of the preceding Paleozoic systems severally is around the outcrops of the older systems. But the outcrops of the Pennsylvanian exhibit no tendency to a similar concentric distribution Rather do they seem to cover areas between the outcrops of the older systems" (Chamberlin and Salisbury). The reason for such differences is not far to seek. For instance

Ordovician rocks are actually more widespread than the Pennsylvanian, but they are largely concealed under later rocks, while the Pennsylvanian rocks were never extensively covered by later deposits (except Glacial drift and to a small extent by Permian strata in the Appalachian district). Shortly after their deposition, toward the close of the Paleozoic, the region was elevated and has remained a land area ever since. Post-Paleozoic erosion has been sufficient to remove much of the Permian and some of the Pennsylvanian, though large areas of the latter rocks still remain as shown on the accompanying map.

Pennsylvanian rocks are extensively developed in western North America from northern Mexico to central Alaska, particularly in the western interior of the United States where they are much folded.

In the Appalachians (Fig. 110), Nova Scotia, and New Brunswick, and in the mountains of the west, the rocks are highly folded or tilted, but in the Mississippi Basin they have remained in almost horizontal position not far above their place of origin.

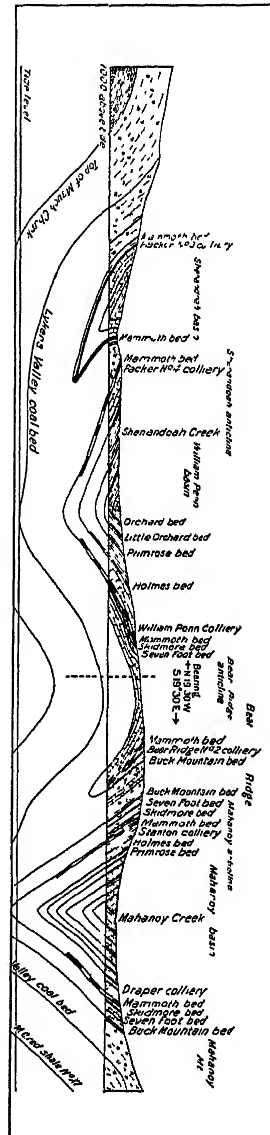


Fig. 110

Geologic structure section through one of the anthracite coal fields of eastern Pennsylvania. Note the number and thickness of the coal beds shown by the heavy black lines, and their sharply folded structure. Length of section, a little over two miles (After Stoek, U S. Geological Survey, 22nd An. Rep.)

Pennsylvanian Rocks in the East. — Rocks comprising this system in the eastern part of North America are partly of marine and partly of non-marine origin with the latter (including coal) unusually prominently developed.

The following extracts from a paper by D. White concisely describe the Pennsylvanian rocks of the Appalachian province (also see Fig. 111): "The *Pottsville*, like the succeeding formations, is composed of sandstones, shales, and clays (including fire clays, coals, and limestones), but it contains a larger proportion of sandstones and arenaceous shales than the later formations . . . The Pottsville is thickest in the southern exposures, where, near the eastern outcrops, it probably exceeds 7500 feet. In the northwestern bituminous area . . . it measures locally less than 200 feet. . . . The Pottsville contains all the workable coals south of the Kentucky-Tennessee state line.

"The *Allegheny*, next succeeding the Pottsville, is a thin formation characterized by a larger proportion of coal, shale, limestone, and iron ore. In the bituminous districts . . . the Allegheny ranges generally between 250 and 350 feet in thickness near the northern outcrop, though it thins southwestward to 160 feet in northeastern Kentucky.

"The *Conemaugh*, which succeeds the Allegheny, is generally marked at its base by sandstone or conglomerate. It is especially characterized by sandstones, shales, and limestones, intermingled, particularly in the western area, with red and green shales, clays, and sandstones. It contains less coal than any of the other Pennsylvanian formations of the Appalachian trough.[1]

"The *Monongahela* is distinguished by its relatively large proportion of coal and limestone, the latter composing over one-third in some districts. The formation . . . averages about 325 feet or less in thickness. Its coals, including the great Pittsburg coal at its base, are of notable thickness and value."[2]

The four distinct subdivisions of the system above described are generally not recognized as such in the Mississippi Basin, but various local names are there given to the subdivisions of the system which is usually thinner and less arenaceous than in the Appalachian district.

[1] A maximum thickness of 800 to 900 feet for the Conemaugh is shown in western Pennsylvania and Maryland

[2] D. White. U S. G. S, *Professional Paper 71*, pp. 431–432.

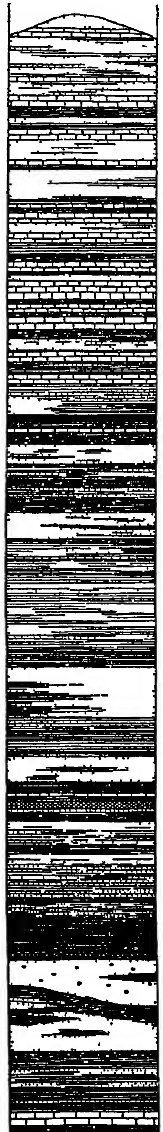
System	Kind of Rock	Columnar section	Thickness in feet
Permian	*Dunkard* sandstone, limestone and coal		300+
Pennsylvanian	*Monongahela* shale, sandstone, limestone and coal		310 to 400
Pennsylvanian	*Conemaugh* shale, sandstone and little coal		600
Pennsylvanian	*Allegheny* shale, sandstone and coal		280
Pennsylvanian	*Pottsville* sandstone and some coal		150
Mississippian	*Mauch Chunk* shale, sandstone and limestone		150

Fig 111

Geologic (columnar) section in western Pennsylvania showing the vertical distribution of coal beds (heavy black bands) and their relations to associated strata. (After Campbell, U. S. Geological Survey, Folio 94.)

Small areas of Pennsylvanian igneous and metamorphosed sedimentary rocks, together with some graphitic coal, occur in Rhode Island and Massachusetts.

Coal-bearing strata of this age, largely shales and sandstones of non-marine origin, attain a thickness of thousands of feet in New Brunswick and Nova Scotia.

In the midst of the Mississippi Basin, especially from Indiana westward to eastern Nebraska and thence southward into Texas, alternating, continental, coal-bearing, and marine strata occur. Not only are these strata as a rule thicker, but also they are more generally of marine origin, than the Pennsylvanian strata of the Appalachian region. Sandstones and shales of this age reach the phenomenal thickness of fully 25,000 feet locally in Arkansas and Oklahoma.

In central Texas the various formations of Pennsylvanian age reach a thickness of 6500 feet. These are listed in the table on a preceding page.

Pennsylvanian Rocks in the West. — In the Rocky Mountains and westward in the United States, the Pennsylvanian rocks are practically all of true marine character and consist largely of limestone and shale with some sandstone and little coal, thus being in marked contrast with the rocks of the system in eastern North America The thick *Wells* limestone of the Idaho region is particularly noteworthy. The Pennsylvanian strata have seldom been subdivided in the far west.

Thickness of the Pennsylvanian. — In the Appalachian district, the system ranges in thickness from about 1500 feet to approximately 10,000 feet. A maximum thickness of 13,000 feet is known in Nova Scotia, and 12,000 feet in Rhode Island. Through the Mississippi Basin the thickness is usually not more than 1000 to 2000 feet, though in Arkansas a thickness of over 25,000 feet has been found. In the western United States the thickness varies much, though it is usually at least several thousand feet.

Igneous Rocks. — Considerable amounts of granite are intruded into the Pennsylvanian and other rocks of Massachusetts, but these may really be of Post-Pennsylvanian age. Also in the Cordilleran region from northern California to Alaska vulcanism occurred on a large scale in Pennsylvanian time, and much volcanic material is there associated with sediments.

Physical History

Early Pennsylvanian. — The Pennsylvanian period was characterized not only by an unusual number of oscillations between land and sea, but also by various diastrophic movements more or less of the nature of mountain-making. Disregarding relatively minor oscillations of level between land and sea, the outstanding feature in regard to the relations of land and water during Pennsylvanian time was progressive submergence of a considerable portion of the continent, beginning in the east and spreading westward and then northwestward to Alaska.

As we learned in the preceding chapter, the Mississippian period closed with a widespread emergence of all of the submerged areas in eastern North America. Very early in the Pennsylvanian the sea began to transgress over the land by extending a long, narrow estuary northward through the Appalachian district as far as Pennsylvania. The Pottsville sandstones and conglomerates, derived by erosion from Appalachia immediately to the east, were deposited to great thickness in this estuary, and it is thus readily seen why the Pottsville should be thickest on the east side. Gradually the early Pottsville basin of deposition expanded and extended over much of the interior region containing Pennsylvanian coal, through central Texas, and westward across northern Mexico to the Pacific Ocean. There was probably a connection between this sea and the Gulf of Mexico through eastern Mexico, and a narrow eastern connection with the Gulf probably existed. Map Fig. 112 shows the situation. The marine waters, except in Mexico, were more or less intermittent with low swampy lands.

Middle and Late Pennsylvanian. — The relations of land and water just described continued nearly the same into early Middle Pennsylvanian (Allegheny) time, but probably the westward connection with the Pacific did not then exist.

Later in Middle Pennsylvanian (Conemaugh) time the sea swept westward over the western interior of the United States to connect with the Pacific Ocean across northern California.

In Late Pennsylvanian (Monongahela) time the sea continued its sweep until the Rocky Mountain region of western Canada and the eastern part of Alaska were covered. Fully one-third of the continent was then submerged as shown by map Fig. 113. Volcanoes were then active between northern California and Alaska.

In the western part of the continent true marine conditions prevailed in Pennsylvanian time, hence there is little coal of this age there. In the east, however, marine, estuarine, lacustrine, marsh or bog, and even land conditions alternated more or less locally in the basins of deposition.

Origin of the Coal Beds. — Since the remarkable physical geography conditions of Pennsylvanian time favored the accumu-

Fig 112

Paleogeographic map of North America during Early Pennsylvanian time. White areas, land, ruled areas, sea. (Principal data, modified by the author, after maps by C. Schuchert)

lation of the world's greatest coal beds, they deserve more detailed discussion. "Perhaps the most perfect resemblance to coal-forming condition is that now found on such coastal plains as that of southern Florida and the Dismal Swamp of Virginia and North Carolina. Both of these areas are very level, though with slight depressions in which there is either standing water or swamp condition. In both regions there is such general interference with

free drainage that there are extensive areas of swamp, and in both there are beds of vegetable accumulations. In each of these areas there is a general absence of sediment and therefore a marked variety of vegetable deposit. If either of these areas were submerged beneath the sea, the vegetable remains would be buried and a further step made toward the formation of a coal bed. Reëlevation, making a coastal plain, would permit the accumula-

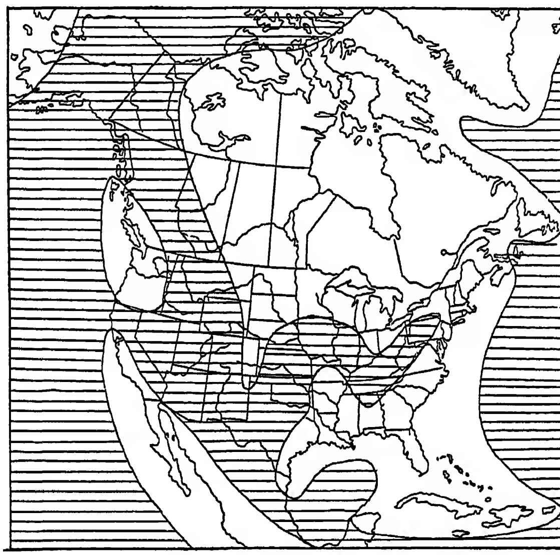


Fig 113

Paleogeographic map of North America during late Middle and Late Pennsylvanian time. White areas, land; ruled areas, sea. (Principal data, modified by the author, from maps by B Willis and C Schuchert.)

tion of another coal bed above the first, and this process might be continued again and again."[1] It is, however, not necessary to assume repeated elevation and subsidence of swamp areas in order to account for numerous coal beds one above another in a given region. A general subsidence, often intermittent (with possibly some upward movements), would occasionally cause the luxuriant

[1] H. Ries: *Economic Geology*, 1910, p. 9.

vegetation of a great swamp area to be killed and allow the deposition of sediment over the site. Then the filling of the shallow water with sediment would allow another bog to be formed, etc. In the coal field of Nova Scotia there are 76 distinct coal beds; in Alabama 35; in Pennsylvania at least 20; and in Illinois 9. Each of these coal beds represents an ancient swamp in which grew a luxuriant vegetation. It should be borne in mind that workable coal seams constitute only about 2 per cent of the containing strata which are sandstones, shales, clays, and, in some localities, limestones.

Perhaps no single coal seam in the world underlies such a large area (12,000 to 15,000 square miles) as the famous Pittsburg coal bed. It is worked over an area of about 6000 square miles, and for 2000 square miles it averages 7 feet in thickness. Most of the swamps or bogs of Pennsylvanian time were much smaller than this.

In the anthracite coal district of eastern Pennsylvania, the famous "Mammoth" coal bed is remarkable for its great thickness up to 50 or more feet.

It may be of interest to consider the length of time necessary for the accumulation of so many coal beds one above the other. A vigorous growth of vegetable matter on an acre has been estimated to produce the equivalent of 100 tons of dried organic matter per century. This amount compressed to the specific gravity (1.4) of coal would cover an acre less than two-thirds of an inch deep. Considering that four-fifths of the organic matter escapes as gases in the process of coal making, we find that it would take nearly 10,000 years to make one foot of coal. Now, since the total thickness of coal beds in the Pennsylvanian system is often from 100 to 250 feet, it is readily seen, on this basis, that the time necessary for the accumulation of the coal deposits was from 1,000,000 to 2,500,000 years. On a conservative basis, the time necessary for the deposition of the sediments was fully as long, so that the Pennsylvanian period appears to have had a duration of no less than 2,000,000 to 5,000,000 years.

Close of the Pennsylvanian. — At the end of the period the remarkable, near sea-level, coal-swamp geographic conditions in the eastern United States were somewhat reduced by emergence of the lands distinctly above sea level. From the Great Plains westward also the marine waters were notably restricted.

In the east, at least, the emergence was probably due to a beginning of the great orogenic movements which culminated in the Appalachian Mountain Revolution at the close of the Paleozoic era.

Foreign Pennsylvanian

Europe. — Viewed in a broad way, the Pennsylvanian of Europe presents certain interesting parallels with North America.

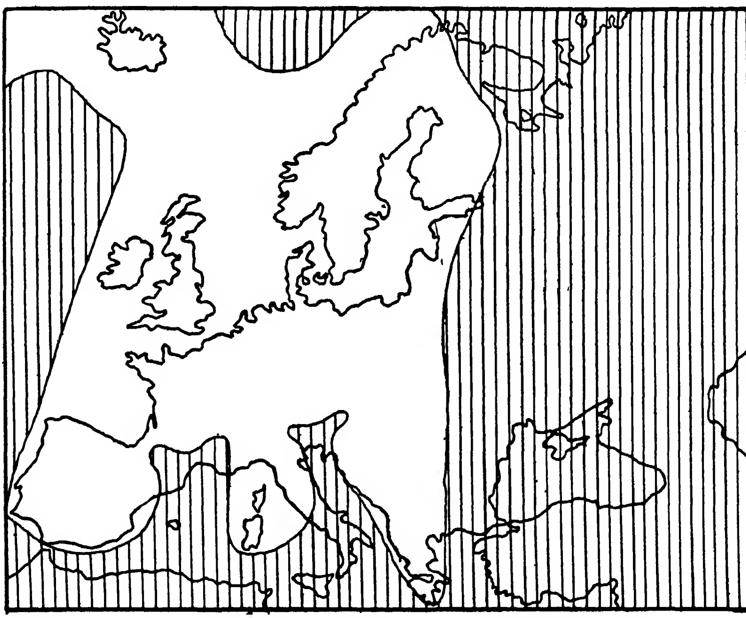


Fig. 114

Sketch map showing the general areas of submergence in Europe during Pennsylvanian time White areas, land; ruled areas, sea. (Modified by the author after F X. Schaffer)

Thus in Europe, sandstone or conglomerate, corresponding to our Pottsville, often lies at the base of the system. Above this, in western Europe, are the Coal Measures consisting of shales, sandstones, and some limestones together with numerous beds of coal, and in every way much like the Coal Measures of eastern North

America (Fig. 111). In eastern and southern Europe the rocks are largely true marine limestones and free from coal, though some coal does exist in southern Russia. Map Fig. 114 shows, in a general way, the principal areas of submergence during Pennsylvanian time.

Igneous rocks were intruded into the strata of western Europe during the Pennsylvanian, the vulcanism probably being a continuation of that begun in the preceding period.

Other Continents. — Much rock of Pennsylvanian age, both of marine and non-marine origin, occurs in Asia, with coal beds in Asia Minor, the east side of the Ural Mountains, and in northern China. The coal beds of China are said to be extensive and important.

Marine strata without coal occur in northern Africa. In the Zambesi district of southern Africa a coal field is known.

In Australia and South America marine and non-marine strata of this age are also pretty widespread. Much coal occurs in southern Brazil.

Climate

Until comparatively recently the plant life of the great coal period was thought to imply a warm to tropical, very moist, uniform climate. More careful study, however, clearly points to a temperate, only relatively humid, but remarkably uniform climate. Some of the criteria favoring this latter view may be stated as follows:[1] The great size and height of the plants together with their frequent succulent nature and spongy leaves indicate luxuriant growth in a moist, mild climate; absence of annual rings of growth shows absence of distinct change of seasons; the presence of aërial roots, by analogy with similar modern plants, implies a moist and warm climate; the nearest present-day allies of the coal plants attain greatest growth in warm and humid climates; at present the greatest accumulations of vegetable matter in bogs and marshes take place in temperate climates where decay is not too rapid and thus suggests a similar climate for the accumulation of the coal deposits; and the remarkable distribution of almost identical plant types in Pennsylvanian rocks from Arctic to tropical regions clearly shows a pronounced uniformity of climate over the earth.

[1] Based upon the work of D. White: *Jour Geol*, Vol. 17, 1909, p. 338.

Economic Products

As already suggested, the principal economic product of Pennsylvanian age is coal, the richest and most extensive coal deposits in the world being of this age. Eastern North America, western Europe, and northern China contain the most important coal fields. The map (Fig. 109) gives a general idea of the locations of the coal fields of eastern North America, though several of the areas of coal-bearing Pennsylvanian rocks are really somewhat larger than this surface distribution (or outcrop) map shows. These areas, largely underlain with workable coal, are as follows: (1) Anthracite field of eastern Pennsylvania — 484 square miles; (2) Appalachian field from western Pennsylvania to Alabama — 70,000 square miles; (3) Eastern Interior field in Indiana, Illinois, and Kentucky — 50,000 square miles; (4) Northern Interior field in Michigan — 11,000 square miles; (5) Western Interior field from Iowa to Oklahoma — 72,000 square miles; (6) Texas field — 13,000 square miles; and (7) Nova Scotia-New Brunswick field — 18,000 square miles. Thus in eastern North America a total of about 235,000 square miles is mostly underlain with workable coal of Pennsylvanian age. Considerable coal of this age also occurs in Alaska.

Iron ores of some importance are found in the carbonate and oxide forms as bedded deposits in Pennsylvanian rocks. Such deposits were formed by precipitation, in the marshes and swamps, of the iron brought down from the lands in soluble form. The principal deposits occur in western Pennsylvania, eastern Ohio, and northern West Virginia.

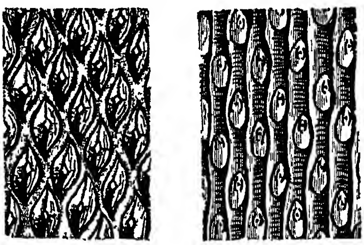
Pennsylvanian rocks also yield considerable oil and gas especially in Illinois, Kansas, and Oklahoma.

Life of the Pennsylvanian

In the preceding Paleozoic chapters, our studies of organisms have been chiefly confined to marine forms because either they only existed, or predominated, or because they have left us the most abundant records. Rocks of the Pennsylvanian system are the earliest to carry abundant records of land plants and animals (Amphibians), and for the first time our principal discussion of the life of a period will deal with such forms. The

Coal Measures and their enclosed organic remains have been studied in unusual detail because of the economic value of the coal

Plants. — The plant life of Pennsylvanian time was very prolific and the records for this period are far more abundant than for any other Paleozoic period, one reason for this unusually full record doubtless being the very favorable conditions for preservation of the flora of the time. Several thousand species of now extinct plants are known from the Coal Measures alone. It must be remembered that most of the important classes of Pennsylvanian plants existed as early as in the Devonian, but these earlier records are much more scant. The known Coal Measures flora consists almost entirely of the higher Cryptogams (*Pteridophytes*) and the lower Phanerogams (*Gymnosperms*), though *Thallophytes* (e g. Algæ) certainly, and *Bryophytes* probably, also existed. From the negative standpoint, the most significant feature was the complete absence of the typical flowering plants (*Angiosperms*) which are today the most common and the most advanced of all plants.



a *b*

Fig 115

Lepidodendron bark (*a*) and Sigillarian bark (*b*), showing arrangement of leaf-scars

Lycopods (giant Club-mosses) were the largest, most abundant, and conspicuous of the forest trees, and they appear to have culminated during this same period. In marked contrast to such a high position, their descendants of today are represented only by a few, small, delicate, trailing so-called Club-mosses and Ground-pines in our forests. Two of the most prominent of the Pennsylvanian Lycopods were the *Lepidodendrons* and the *Sigillarians.* The *Lepidodendrons* ("scale-trees") had leaf-scars or scales arranged spirally around the trunks of the trees (Fig. 115a). They generally attained a height of 50 to 100 feet and a diameter of 2 to 4 feet. The tall trunks were slender and they branched dichotomously (by twos) only at a considerable height. Long, stiff, needle-shaped leaves were thickly set on the branches. The dropping of the leaves from the older (trunk) portions caused

the leaf-scars or scales above mentioned. Inside of the outer bark, the stem consisted of pithy or loose cellular tissue. Over 100 species of the Lepidodendron are known. The *Sigillarians* ("seal-trees") are so called because of seal-like markings (Fig. 115b) which were arranged vertically on the tree trunk. They were even larger than the Lepidodendrons, having attained a height of 100

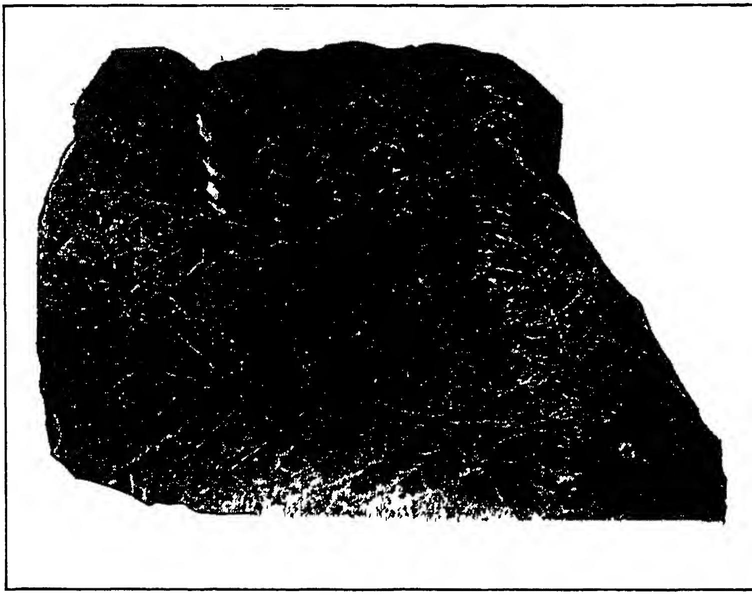


Fig. 116

A Pennsylvanian Pteridosperm, *Mariopteris*. (After D White, U. S. Geological Survey, Monograph 37)

feet or more and a diameter of 5 or 6 feet. The trunk seldom branched and it ended with a rounded tip. In other respects these trees were much like the Lepidodendrons.

Equisetæ ("Horse-tail" plants) were also common in the Pennsylvanian forests. These plants had long, slender, segmented stems which were either hollow or filled with a large, soft pith (Fig. 118). The leaves, which were arranged in whorls around the stems at the joints, were of variable shapes and sizes, usually either needle-like, scale-like, or strap-like. The outside of the stem had a

sort of finely fluted structure but without scars and not continuous as in the Sigillarians. They reached heights of 60 to 90 feet and diameters of 1 or 2 feet. Equisetæ are today chiefly represented by only a few species of rush-like forms not over a few feet high, though in South America some very slender forms grow to heights of 30 or 40 feet.

Filicales (true Ferns) were fairly common and diversified, both as tree-like forms and as small, herbaceous forms. Both forms were very similar in appearance to those now living in tropical and temperate climates (Figs. 116–117).

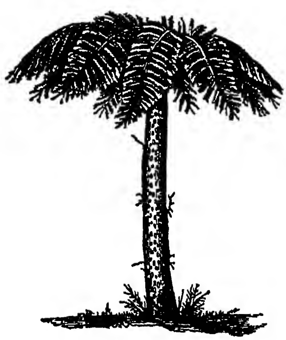


Fig. 117

A living Tree-fern. (From Le Conte's "Geology," permission of D. Appleton and Company)

Pteridosperms ("Seed ferns"), which were common in the Pennsylvanian, comprised a remarkable group of plants recently regarded as transitional between the Cryptogams and Phanerogams. They possessed seeds but not flowers and showed many features which seem to make them the connecting link between the Filicales and the Cycads, hence the name "Cycadofilicales" The seeds were arranged on the leaves. There is considerable difference of opinion concerning the relations and affinities of this remarkable group of plants, now long extinct (Fig. 119).

Gymnosperms. — Of these the most abundant representatives were the *Cordaites.* They were comparatively slender trees which attained a diameter of 2 or 3 feet and a height of 90 feet or more (see Fig. 120). The branches, which were given off only toward the top of the trunk, were supplied with numerous, long, very simple, parallel-veined, strap-shaped leaves notable for great size, sometimes 5 or 6 feet long and 5 or 6 inches wide. The trunks were covered with thick bark, while inside there was much pith. Many specimens have been well preserved. They were important contributors to the formation of some coal beds. They possessed certain features or structures of the Seed-ferns, Conifers, Cycads, and Ginkgos in addition to their own characteristics. Cordaites thus afford a fine illustration of a generalized type of plant, that is to say one

which combined the characters of several distinct (some later) forms.

True *Cycads* and *Conifers* are not certainly known to have existed in the Pennsylvanian period, though some primitive Cycad-like plants probably did.

Invertebrates. — Unless otherwise stated the classes of Penn-

Fig. 118

A Permo-Carboniferous landscape, showing some of the most conspicuous plants of the great Coal Age Lepidodendrons (with branches) and Sigillarians (without branches) in the left background; Equisetæ (segmented) on the right; Seed-ferns in the left foreground; two Amphibians (*Eryops*) on the land; a primitive Reptile (*Limnoscelis*) in the water; and a great Insect (Dragon-fly) in the air. (From a drawing by Prof. S. W. Williston)

sylvanian Invertebrate animals were much the same as those of the middle Paleozoic periods. Only certain notable differences, particularly those of evolutionary significance, will be pointed out.

Foraminifers were very abundant as proved by the vast numbers of tiny wheat-like shells which contributed much to

building up certain Pennsylvanian limestones in America, Europe, and other continents.

Of the *Pelmatozoans* (stemmed Echinoderms) only the *Blastoids* and *Crinoids* remained, the former having become extinct during the period. The *Crinoids* showed a remarkable falling off after

Fig. 119

A Pteridosperm or Seed-fern. Restored by D H. Scott and J. Allen. (From Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

their culmination in the Mississippian, but in the Mesozoic they regained prominence.

Brachiopods were still common but by no means as prominent as in earlier Paleozoic periods. They were much like the Mississippian forms. A noteworthy fact was the almost world-wide distribution of some of the species, which indicates either actual land bridges or at least shallow water areas connecting all the continents.

Among the *Gastropods*, it is important to note that several

species of the earliest known land (air-breathing) Snails have been found.

Cephalopods, both *Nautiloids* and *Ammonoids* were much as in the Mississippian, though the latter showed gradually increasing complexity of suture structure (Fig. 121).

Trilobites were few and unimportant and close to the period of their extinction.

Eucrustaceans of Shrimp-like and Crayfish-like forms were present but not common (Fig. 122).

Arachnids were well represented by both *Spiders* and *Scorpions*, the former having made their first known appearance. They looked much like existing forms (Fig. 123). *Eurypterids* still continued though not in abundance. Their common associations with land and fresh-water plants and animals clearly proves many at least to have been fresh-water dwellers.

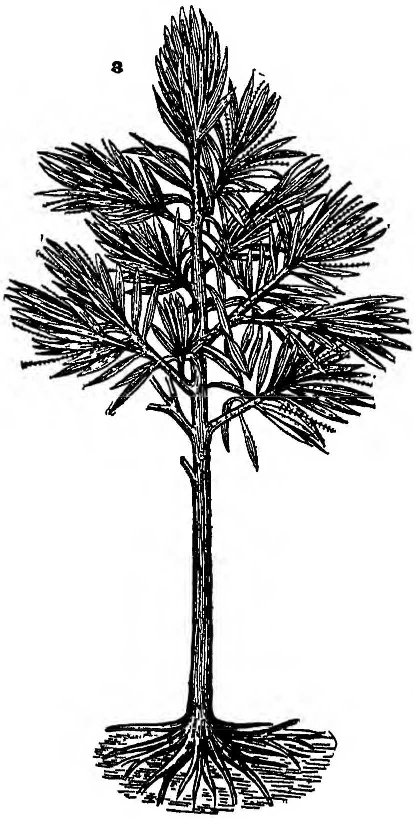


Fig. 120

Cordaites restored (From Schuchert's "Historical Geology," courtesy of John Wiley and Sons)

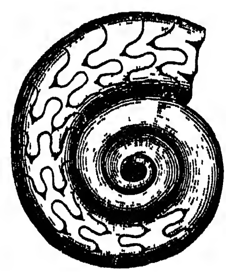
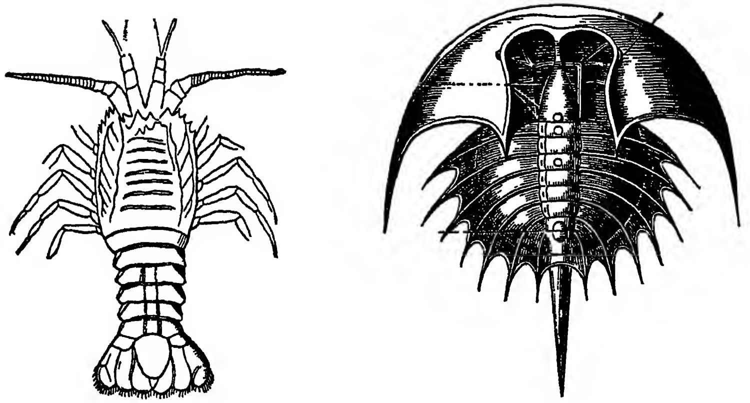


Fig. 121

A Pennsylvanian Goniatite (*Goniatites lyoni* After Meek.)



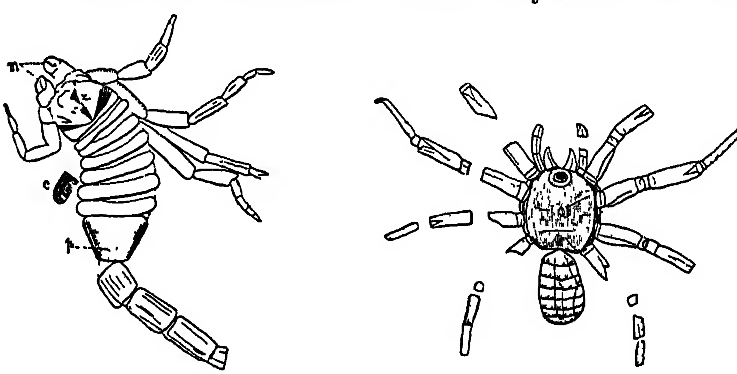
a *b*

Fig 122

Pennsylvanian Eucrustaceans: *a*, *Anthrapalæmon gracilis* (Meek and Worthen), *b*, *Euproops danæ* (Meek and Worthen) (From Le Conte's "Geology," permission of D Appleton and Company)

Myriapods were plentiful.

Insects, including the oldest known fossil forms, occur in Pennsylvanian rocks. Their appearance marked a notable advance in the evolution of Invertebrate life because they include the most



a *b*

Fig. 123

Pennsylvanian Arachnids: *a*, Scorpion, *Eoscorpius carbonarius* (Meek and Worthen); *b*, Spider, *Anthrolycosa antiqua* (Beecher). (From Le Conte's "Geology," permission of D. Appleton and Company.)

highly organized of these creatures. As would be expected in accordance with the abundant and favorable plant environment, the Insects showed a notable development. Hundreds of species are known from the Coal Measures of America alone. Nearly all were of simple types belonging to the Orthopters and Neuropters, which orders are represented by modern Grasshoppers, Cockroaches, Caddisflies, etc. Somewhat higher types may possibly have been present, but the highest Insects, such as Butterflies, Bees, Ants, etc., are not known to have existed. Two other noteworthy facts

Fig. 124

A Pennsylvanian Insect, *Corydaloides scudderi* (Brongniart). This Insect had a spread of wing of 18 inches. (From Le Conte's "Geology," permission of D Appleton and Company.)

regarding Pennsylvanian Insects are: (1) Their great size, some having had a spread of wing of from 1 to 2½ feet (Fig. 124); and (2) the existence of three pairs of wings on some species. Probably the most common of all Pennsylvanian Insects were the Cockroaches, hundreds of species being known. Some specimens are several inches long.

Vertebrates. — *Fishes* continued much the same as in the Mississippian.

Amphibians for the first time left abundant records in the Pennsylvanian rocks, and they merit special discussion here. This was probably the culminating period of the Amphibians, and from the standpoint of the evolution of the air-breathing Vertebrates

the Pennsylvanian is regarded as a very important period in geological history. It is to be remembered that the earliest Amphibians almost certainly evolved from certain types of Fishes. All Mississippian and Pennsylvanian Amphibians are often classed together as *Stegocephalians*, so called because of the relatively large, bony, roof-like plates of the skulls.

As regards the principal forms of Amphibians of Pennsylvanian time, the writer can do no better than to quote an excellent summary by S. W. Williston:[1] "The predominating types of the

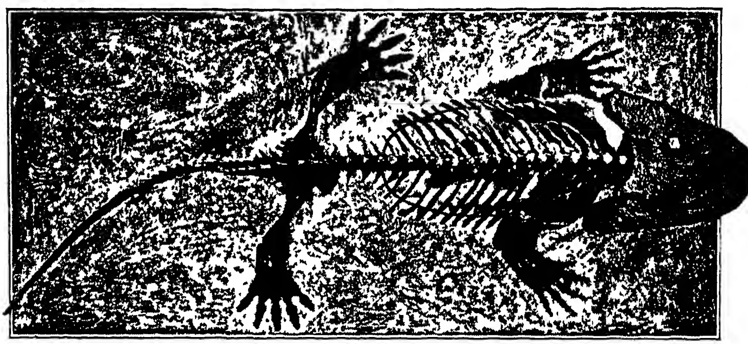


Fig 125

A Pennsylvanian Amphibian (Labyrinthodont), *Eryops* This creature attained a length of 6 or 8 feet (Courtesy of the American Museum of Natural History.)

Pennsylvanian were what we usually call the *Branchiosaurs* and the *Microsaurs*, for the most part small or very small creatures, at least as small as their nearest living relatives of the present time, the Salamanders. We are quite justified in the belief that their habits in general were not greatly unlike these descendants, rather sluggish creatures living about or in the water, for the Branchiosaurs at least passed through larval stages. They were more or less protected by an external bodily armor against their enemies, whether of their own or other kinds, in all probability terminating their existence as distinctive types long before the close of the Paleozoic. But among them there were some classed with the heterogeneous group which we call Microsaurs, which had made a very distinct advance, both toward a higher existence and away

[1] *Outlines of Geologic History*, 1910, p 164.

from the water. . . . Some lost the dermal armor completely and became fleet of movement, as is evidenced by the structure of the limbs, limbs mimicking in form and structure so closely those of modern quick-running Lizards as to be practically indistinguishable."

The *Labyrinthodonts*, and certain other closely related forms, comprised another important group of Pennsylvanian Amphibians. They are so named because of the peculiar, labyrinthine, internal tooth-structure (Fig. 126). They were the gigantic land Vertebrates of the period, some having reached a length of 7 or 8 feet (Fig. 125).

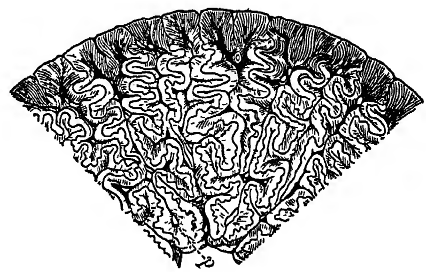


Fig 126

Transverse section of a Labyrinthodont tooth (After Owen from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

Reptiles. — Whether or not true Reptiles existed in this period depends largely upon the classification of the primitive land Vertebrates. The abundance of true Reptiles in the succeeding (Permian) period strongly suggests their earlier differentiation from the Amphibians. According to Williston. "We may be assured that some of them (Amphibians), before the close of the Pennsylvanian, were inhabitants of high-and-dry land regions where fleetness of movement, rather than obscurity, preserved them from their enemies, crawling Reptiles in everything save some insignificant technical details of their plates."

CHAPTER XII

THE PERMIAN PERIOD

Origin of Name, Subdivisions, Etc.

This period was so named by Murchison in 1841 because of the widespread development of rocks of this age in the Russian province of Perm. It is rather distinctly a transition period between the Paleozoic and Mesozoic eras. In both the eastern and western United States the Pennsylvanian rocks usually grade upward into the Permian, while in the western interior region the Permian and Triassic strata are often much alike. Thus it is often difficult to sharply separate the Permian from the systems immediately above and below it, and the delimitation of the Permian system in western America is by no means a settled matter at the present time. The scarcity or absence of fossils in many of the western areas adds to the difficulty.

The following table will give a general idea of the subdivisions now recognized in some of the better known regions, though it must be clearly understood that precise correlations are not meant to be implied.

	Texas	*Kansas*	*Pennsylvania*	*Grand Canyon*
	(Little or no very late marine Permian in North America)			
Permian System	Double Mountain (Salt, gypsum, and limestone) Clear Fork (Limestone and red clay) Wichita (Red clay, sandstone, and limestone).	Cimarron (Red Beds) (Sandstones, shales, dolomites, and gypsum) Wellington (Various strata). Big Blue (Shales and limestones).	(Missing) Dunkard (Sandstones, shales, limestones, and some coal)	Kaibab (White limestone). Coconino (Gray sandstone). Supai (Red sandstone and shale).

Distribution and Character of the Rocks

General Distribution. — Compared with the preceding Paleozoic systems, the Permian rocks have a rather limited distribution. There are small areas in Nova Scotia and New Brunswick; a small area in Pennsylvania, Ohio, and West Virginia; large areas in Arizona, New Mexico, Texas, Oklahoma, Kansas, Colorado, Nebraska; and some smaller areas in Colorado, Utah, Nevada, California, Idaho, Montana, southwestern Canada, and Alaska. Most of these surface exposures are within the areas represented on the map (Fig. 130) as occupied by marine waters.

In the western United States the Permian strata are considerably more extensive than their surface distribution because they are concealed under Mesozoic or Cenozoic rocks over large areas. Also there is some reason to think that the Permian strata formerly extended over much of the Great Basin region, but have been removed by erosion, leaving much Pennsylvanian or Mississippian rock now at the surface. In the eastern United States, however, the one small area in the northern Appalachian district comprises all of the Permian except possibly some in the lower Mississippi Valley where Mesozoic and later rocks effectually conceal the older rocks.

Character of the Rocks. — The Permian strata (Dunkard series) in the small area of the northern Appalachian district are sandstones and shales, together with some limestone and coal beds. They are in every way much like the Coal Measures just below.

In Kansas the Permian rocks are divisible into two rather distinct series, the lower or Big Blue series of shales and limestones being largely marine, while the upper or Cimarron series of sandstones, shales, limestones, salt, and gypsum are mostly not truly marine and they are characterized by a prevailing red color.

The Texas Permian strata are chiefly red beds of mostly nonmarine origin and divisible into three series as shown above. Red and blue shales, limestones, and sandstones, with some gypsum, constitute the two lower series, while red sandstones, shales, salt, and gypsum chiefly make up the upper series.

The salt beds of Kansas, Oklahoma, and Texas underlie an area of fully 100,000 square miles, reaching a thickness of more than 1000 feet in Texas (see Fig. 129). Recently there have been dis-

covered in the Permian of western Texas potash deposits of considerable extent.

Strata, mostly of non-marine origin and containing much red

Fig 127

A detail view of Permian (Kaibab) limestone at the rim of the Grand Canyon of Arizona Most of the rock in the distance is of Paleozoic age (Courtesy of the U S. Geological Survey)

materials like those of Texas and Kansas, are also found through New Mexico, western Colorado, and Wyoming (see Fig. 128).

In the states farther west, including Arizona, Utah, Idaho, Nevada, and northern California, there are considerable marine Permian formations. Three marine formations — Supai red sandstone and shale, Coconino gray sandstone, and Kaibab white limestone (at the top) — constitute the upper 2000 feet of the walls of the Grand Canyon of Arizona.

True marine strata, some thousands of feet thick, are known in Alaska, especially in the Copper River region.

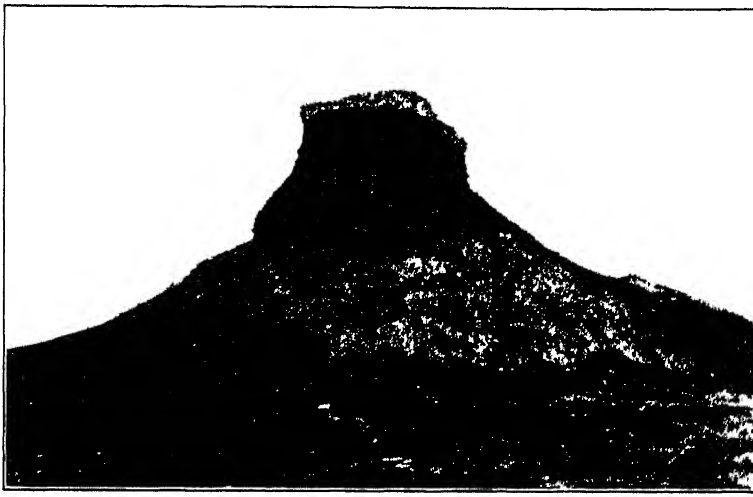


Fig 128

Late Permian or early Triassic "Red Beds" in Red Butte, eastern Wyoming The bright red strata are capped by a 30-foot layer of white gypsum (After Darton, U S Geological Survey, Folio 127)

In Nova Scotia and New Brunswick the Permian also consists mostly of red beds including conglomerates, sandstones, and shales.

Thickness of the Permian. — In Pennsylvania and Ohio the Dunkard series (Lower Permian only) shows a thickness of about 1000 feet. A thickness of 2000 feet for the whole system is reported from Kansas; 5000 to 10,000 feet in Texas; and 3800 feet in Utah. In Nova Scotia and New Brunswick Permian strata attain a maximum thickness of 8000 feet.

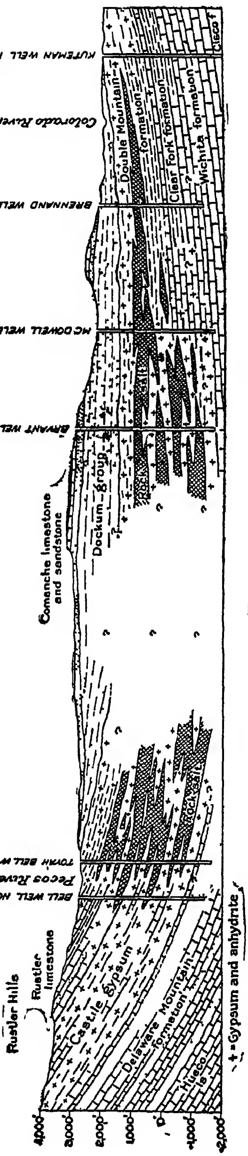


Fig 129

East-west structure section in western Texas showing the stratigraphic relations of the great salt beds of Permian age Length of section, 200 miles Vertical scale, greatly exaggerated The Permian formations lie between the Hueco (Pennsylvanian ?) and the Dockum (Triassic) (After W H Hoots, U S Geological Survey)

Igneous Rocks. — Plutonic igneous rocks (mainly granites) of Permian, and possibly somewhat earlier, age occur in numerous large and small bodies in the Piedmont Plateau and so-called older Appalachians, especially in their southern portions, and also in New England, New Brunswick, Nova Scotia, and Newfoundland.

Physical History

During the Period. — Combining the above descriptions of rock distribution and characters with an examination of the paleogeographic map, the physical history of North America during the Permian may be readily comprehended.

The Late Pennsylvanian sea seems to have continued, somewhat restricted, into earliest Permian time, thus the relations of land and water in North America were still much as shown on map Fig. 113. Soon, however, the waters became much more restricted as a result of the disappearance of the arm of the sea from the Appalachian region westward to Kansas, and

also the withdrawal of the waters from Montana to central Alaska. The extent of the waters was then — late Lower and Middle Permian time — about as represented on map Fig. 130.

Into the southwestern interior sea a bold peninsula, called the Ancestral Rockies, extended from South Dakota to western Texas. A more or less cut off arm of the sea or basin lay just east of this peninsula. In this basin, lying in an arid region,

Fig. 130

Paleogeographic map of North America during late Lower and Middle Permian time. White areas, land; ruled areas, sea. (Principal data, modified by the author, from maps by B. Willis and C Schuchert)

the conditions were favorable for the deposition of the so-called Red Beds and associated great beds of salt and gypsum.

By Late Permian time the southwestern interior sea seems to have vanished, leaving wide areas favorable for continental deposition.

No very late Permian marine rocks are known in North America and, as far as known, the whole continent was a land area by the close of the period.

The Early Permian rocks of the northern Appalachian district clearly prove a continuation of the Coal Measures conditions, that is great fresh-water swamps or basins, with occasional sea incursions.

The Nova Scotia and New Brunswick Permian rocks are also chiefly of continental origin, suggesting conditions of deposition similar to those in Texas and Kansas, except that salt and gypsum are practically absent.

Close of the Permian (Appalachian Revolution). — The Paleozoic era was brought to a close by one of the most profound physical disturbances in the history of North America. It has been called the Appalachian Revolution because at that time the Appalachian Mountain Range was born out of the sea by upheaval and folding of the strata. Perhaps it would be better to say that the revolution reached its climax at about the close of the Paleozoic because the evidence is clear that the upward movement began at least as early as the Pennsylvanian, and slowly increased to the close of the era. Since Permian strata are involved in the folding along the western side of the Appalachians, we know that much of the disturbance must have occurred after the deposition of those strata

All through the vast time (many millions of years) of the Paleozoic era, a great land-mass (Appalachia) existed along what is now the eastern coast of the United States. Its western boundary was, most of the time, just east of the present Appalachians, while it must have extended eastward at least as far as the border of the continental shelf Concerning the altitude and the character of the topography of Appalachia we know almost nothing, but we do know that it consisted of rock of pre-Cambrian age. The enormous amount of sediment derived from it shows that Appalachia was high enough during nearly all of its history to undergo vigorous erosion. Although oscillations of level more than likely affected the land-mass, and its western shore line was quite certainly shifted at various times, nevertheless it persisted as a great land area with approximately the same position during all of its long history. Its general position is well shown on the various Paleozoic paleogeographic maps.

Barring certain minor oscillations of level, all of the region just west of Appalachia was occupied by sea water during much of the Paleozoic era, and sediments derived from the erosion of Appa-

lachia were laid down layer upon layer upon that sea bottom. The coarsest and greatest thickness of sediments deposited nearest the land, that is along what we might call the marginal sea bottom. At the same time, finer sediments and limestones in thinner sheets were being deposited over much of the Mississippi Valley region. By actual measurement, in the present Appalachians, we know that the maximum thickness of these sediments was at least 25,000 feet. Now, since these are all of comparatively shallow water origin, as proved by the coarseness of sediments, ripple-marks, fossil Coral reefs, etc., we are forced to conclude that this marginal sea bottom gradually sank during the process of sedimentation, thus producing what is called a great geosynclinal trough. Perhaps the very weight of accumulating sediments caused this sinking. Finally, toward the close of the Paleozoic era, sinking of the marginal sea bottom and deposition of sediments ceased, and a tremendous force of lateral compression was brought to bear, causing the strata to become folded and more or less fractured. Thus arose the great Appalachian Mountain range which, in its prime, was doubtless much loftier than it is today (see Fig. 131).

This tremendous deformation took place very slowly, though during a short time as compared with the length of the Paleozoic era. As soon as the folds appeared well above sea-level, irregularities began to be carved out by the work of erosion so that even from early youth the mountains presented a rugged surface. Mountains now in process of growth, like the Coast Ranges of California, show such ruggedness. The great thrust faults, especially of the southern Appalachians where certain great rock masses have been pushed for miles over others, were not produced by single movements but rather by many repeated movements along the same thrust planes (see Fig. 132).

Important orogenic movements through New England and to Newfoundland are known to have taken place at the same time. Accordingly the whole eastern side of the continent, for a distance of 2000 miles, was profoundly affected by mountain-making disturbances.

The Appalachian Revolution was accompanied by tremendous intrusions of granite magma throughout New England, New Brunswick, and Newfoundland, and to the east of the Appalachian Mountains proper, particularly in the Piedmont Plateau and the so-called "Older Appalachians." The granite is now widely ex-

posed in these regions. An important factor contributing to the present-day height and ruggedness of northern New England and of the southeastern "Older Appalachian" region is the outcrop-

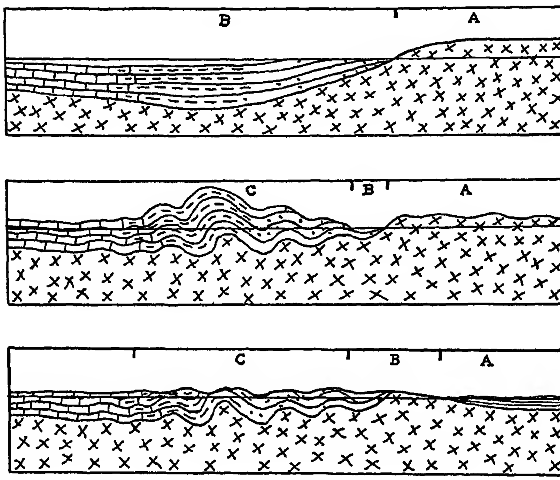


Fig 131

Highly generalized structure sections across the Appalachian Mountains and adjoining districts to illustrate certain important features in the history of the region.
Upper figure: *A*, Appalachia; *B*, marginal sea-bottom (Appalachian geosyncline) mostly filled with sediments derived from Appalachia during Paleozoic time.
Middle figure The same region with the strata folded into mountains as they would have appeared, if unaffected by erosion, toward the close of the Paleozoic era *A*, Appalachia, *B*, Triassic basin or downwarp; *C*, Appalachian Mountains.
Lower figure. The same region as it now appears after much erosion, the submergence of Appalachia, and the deposition of the Coastal Plain beds *A*, Coastal Plain; *B*, Piedmont Plateau, *C*, Appalachian Mountains. (By the author)

ping of so much of this resistant granite. The two regions last mentioned are the highest and most rugged in eastern North America, the highest peak of all being Mt. Mitchell in North Carolina with an altitude of 6711 feet.

Other important geographic changes in addition to the above were (1) the warping of the surface of Appalachia as we shall show in our discussion of the Triassic period; (2) the uplift of the Mississippi Basin, mostly without folding of the strata, east of the Great Plains never again to become submerged to the present time except along the Gulf Coast, (3) the elevation of the Ancestral Rockies from South Dakota to western Texas; and (4) the elevation and erosion of many of the Permian areas west of the Rocky Mountains in the United States, which thus accounts for a rather widespread unconformity between the Permian and Triassic in those areas.

Foreign Permian

Europe. — The Permian of Europe also shows two rather distinct phases — marine and non-marine — but the system in central and western Europe is usually separated from the underlying Upper Carboniferous (Pennsylvanian) by unconformity, thus presenting a contrast to North America. Early in the Permian a great salt lake (or series of lakes), sometimes with local fresh-water conditions, extended over western to central Europe from Ireland to central Germany. Red beds, consisting of sandstones, shales, marls, salt, and gypsum, together with some coal beds, were formed in these inland water bodies. Fossils prove that marine waters sometimes spread over at least portions of this inland basin. Glacial deposits have recently been discovered toward the base of the Permian in Germany. Another feature of special inter-

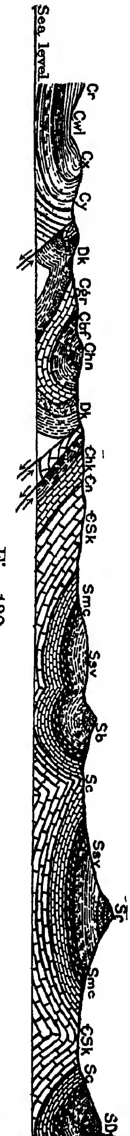


Fig 132

Structure section through a portion of the Appalachian Mountains of western Virginia showing the typical deformation of Paleozoic strata. Length of section, 12 miles. *Chk* and *Cn* = Cambrian; *Csk* = Cambro-Ordovician; *Sc*, *Smc*, *Ssv*, *Sb* = Ordovician; *Sr* = Silurian; *SDg* = Siluro-Devonian; *Dk* = Devonian; and *Cgr*, *Cbf*, *Cy*, *Chn*, *Cx*, *Cwl*, *Cr* = Mississippian and Pennsylvanian (After Campbell, U S. Geological Survey, Folio 44.)

est is the large amount of igneous rock in the form of lava flows, dikes, and tuffs in the Lower Permian, particularly in the British Isles, Germany, France, and the Alps.

Where the Lower Permian occurs in southern Europe, it is mostly of marine origin.

About the beginning of the Upper Permian, marine waters appear to have prevailed over the enclosed basin areas of central

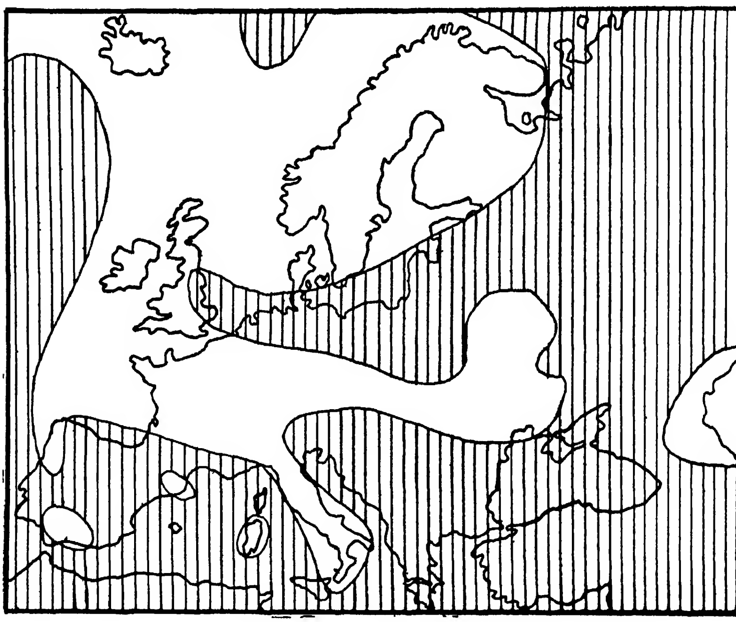


Fig 133

Sketch map showing the relations of land and water in Europe during later Permian time White areas, land, ruled areas, sea (Modified by the author after F X. Schaffer)

and western Europe (Fig. 133), but soon again those waters withdrew to restore salt lake conditions. Neither coal nor igneous rock occurs in the Upper Permian, but the greatest salt beds in the world were deposited in northern Germany during late Permian time. Some layers of magnesium and potassium salts were deposited with the common salt, one well having penetrated the

deposit near Berlin to a depth of 4000 feet without reaching the bottom.

Upper Permian rocks do not occur in France, and where found in southern Europe they are largely marine.

In Russia, the type region for the Permian, rocks of this age underlie much of the country and appear at the surface over a wide area in the eastern part, just west of the Ural Mountains. These rocks are usually conformable upon the Upper Carboniferous (Pennsylvanian). Non-marine deposits, including red beds with salt and gypsum, are common, though at some horizons true marine strata prove incursions of the sea.

Other Continents. — In many other parts of the world Permian rocks are extensively developed, particularly in northern Asia, China, Persia, northern India (including the Himalayas), South Africa, Australia, Tasmania, New Zealand, Argentina, and Brazil. Continental deposits are common. A most remarkable feature is the widespread occurrence of thick (sometimes from 1000 to 2000 feet) glacial deposits in the Permian system in low-latitude countries such as India, South Africa, southern Brazil, and Australia. Furthermore, the plain inference from the close association of certain of these glacial deposits with marine strata is that *glaciers near the equator came down near or actually to sea-level.*

In some countries, as South Africa, Brazil, and Australia, coal beds also occur within the Permian.

Climate

From the above descriptions it is evident that the Permian presents a remarkable combination of climatic conditions, including extensive glaciation, widespread aridity, and conditions favorable for prolific growth of coal-forming plants, all in a single period. Thus the climate of the Permian stands out in striking contrast against the mild and uniform climate of the immediately preceding period. The concentration of the extensive glaciation over low-latitude countries, instead of high-latitude regions, is at present without adequate explanation. It must be confessed that the perplexing problems of Permian climate are as yet far from solved.

Economic Products

As already suggested, coal beds of considerable economic importance occur in the Permian of the northern Appalachian

belt, France, Germany, Bohemia, Australia, Transvaal, and Brazil.

Salt is obtained from the Permian strata of Kansas, Oklahoma, and central Europe.

Gypsum deposits, which are so widespread in rocks of Permian age, are quarried in many states as Iowa, Kansas, Oklahoma, Texas, New Mexico, South Dakota, and Colorado.

The recently discovered potash deposits in the Permian of Texas bear promise of great commercial value.

There are also important gypsum and potash deposits in Europe.

Life of the Permian

As compared with the preceding Paleozoic periods, the Permian shows a decided decrease in numbers and diversity of organisms. The known animal species of the period are to be reckoned by hundreds only. The organisms of the Permian were in several ways distinctly transitional in character between those of the Paleozoic and Mesozoic eras.

Plants. — All the principal groups of *Cryptogams* were represented much as in the Pennsylvanian, except that the *Lycopods* were very greatly reduced. In fact the *Lepidodendrons* became wholly extinct by the close of the period. The *Equisetæ* and *Ferns* continued to be prominent, the Tree-ferns particularly becoming more common.

From the standpoint of evolution, the most interesting changes or advances occurred among the *Gymnosperms*. In addition to the *Cordaites*, which continued from the Pennsylvanian, *Cycads* [1] and *Conifers* are known for the first time, thus giving the flora a decided Mesozoic aspect. The introduction of the Cycads and Conifers marked a distinct advance in the plant world, the Cycads having evolved from the Seed-ferns, and the Conifers from Cordaites.

Invertebrates. — Unless otherwise stated the Invertebrates were in general much like those of the other later Paleozoic periods. There were of course many species changes.

Foraminifers continued to be very abundant as shown by their

[1] In this book the term "Cycad" is used in a broad sense to include the more primitive forms known as Cycadeoids.

presence in marine limestones. *Radiolarians* were present though they are not well known as fossils.

Corals showed an important change in their evolution because of the first appearance of more modern Hexacoralla, or forms whose septa or dividing walls were six in number or multiples of six. The Paleozoic Tetracoralla, however, still continued to be common.

Brachiopods continued to be common with straight-hinged types, so abundant through the Paleozoic era, still prevalent for the last time.

Pelecypods continued to increase in numbers and species, while *Gastropods* much like the older Paleozoic forms were still common.

Among the *Cephalopods* some early Paleozoic types of *Nautiloids* (e.g. *Orthoceras* and *Gyroceras*) still persisted and various species of the modern genus *Nautilus* were added. The *Ammonoids* show the most interesting evolutionary changes, because of the notably increased complexity of their partition or suture structures. A good example is shown in Fig. 134 which is really more suggestive of Mesozoic Ammonites than of Paleozoic Nautiloids.

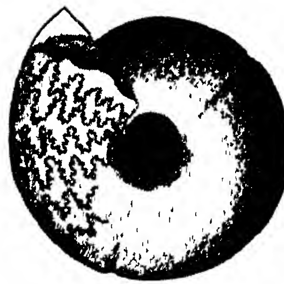


Fig. 134

A Permian chambered Cephalopod, *Waagenoceras cumminsi* (White) showing highly folded suture (partition) lines

Among the *Crustaceans* and *Arachnids* the groups of *Trilobites* and *Eurypterids* became extinct. In fact they had but few representatives in the Permian.

Insects have been found in abundance, especially in the Permian of Kansas and, though the species are different, they were much like those of the Pennsylvanian.

Vertebrates. — *Fishes* were in general very similar to those of the Mississippian and Pennsylvanian, though there were various species and genera changes.

Amphibians. — In general it may be said that the Permian Amphibians were much like those of the Pennsylvanian, except that some were even larger, new species were added, and even more reptilian features were developed in some.

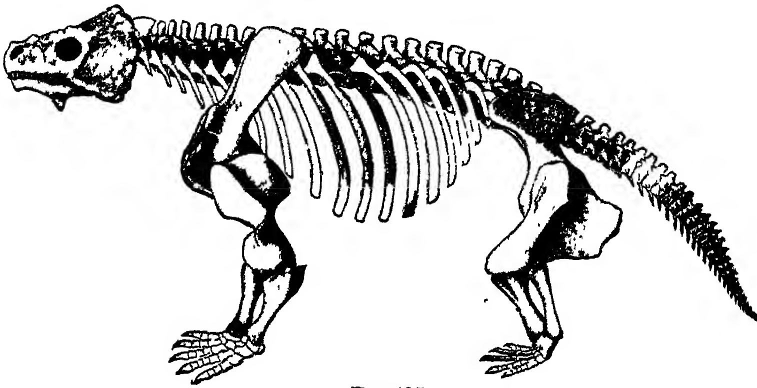


Fig. 135

A Permian Reptile, *Pareiasaurus serridens*. This creature reached a length of over 8 feet. (After Broom, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

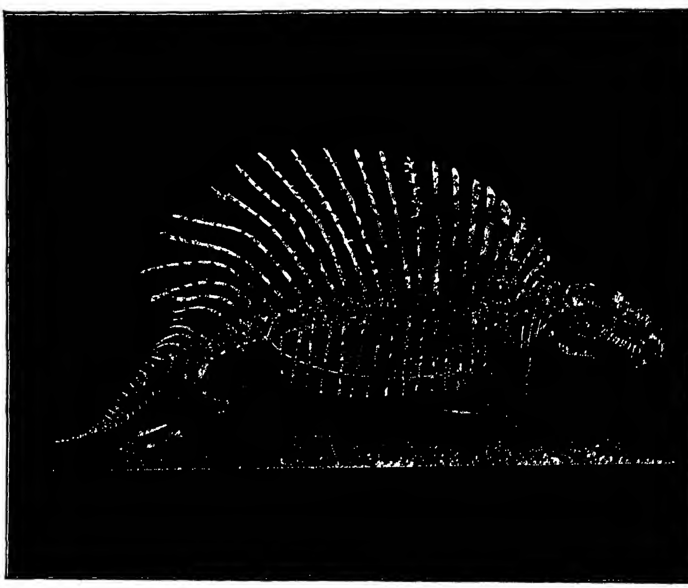


Fig. 136

A Permian Reptile (Pelycosaurian), *Naosaurus claviger*. (After Osborn, from Scott's "Geology," permission of The Macmillan Company.)

Reptiles. — There may be doubt about the existence of true Reptiles in the Pennsylvanian, but there is no question about the abundant reptilian records of the Permian. They developed in a remarkable manner, so that before the close of the period several important subclasses or orders, represented by many individuals, were evolved. Some of the Reptiles already began to show rather distinct mammalian characteristics. The accompanying figures will give a good idea of two important Permian forms.

CHAPTER XIII

SUMMARY OF PALEOZOIC HISTORY

"We have defined geology as the history of the evolution of the earth. *Evolution*, therefore, is the central idea of geology. It is this idea alone which makes geology a distinct science. This is the coherent principle which unites and gives significance to all the scattered facts of geology — which cements what would otherwise be a mere incoherent pile of rubbish into a solid and symmetrical edifice. It seems appropriate, therefore, that at the end of the long and eventful Paleozoic era we should glance backward and briefly recapitulate the evidences of progressive change (evolution)."[1]

Paleozoic Rocks

Paleozoic rocks are dominantly sandstones, conglomerates, shales, and limestones of typical, marine, sedimentary character, though continental deposits also are common, such as fresh-water, swamp, or lagoon deposits of the Pennsylvanian in the eastern Mississippi Basin and the "Red Beds" formed in great salt lakes of Permian age in the southwestern United States

The marine strata furnish abundant evidence, by the presence of ripple and wave-marks, the coarseness of the clastic materials (conglomerates and sandstones), etc., that they were deposited in shallow (epicontinental) seas, and never in really deep ocean water. Continental deposits are also abundantly represented.

In Europe the estimated maximum thickness of Paleozoic strata is 75,000 to 100,000 feet. It must be remembered, however, that this does not mean that such a great thickness of strata is present in any one locality, but rather that this represents the sum-total of the greatest thicknesses of the different formations of the continent.

A thickness of more than 25,000 feet of strata (largely clastic) actually piled layer upon layer may now be seen exposed in the

[1] J. LeConte. *Elements of Geology*, 5th Ed., p. 421.

highly folded and eroded Appalachians, while the maximum thickness of strata there must be between 40,000 and 50,000 feet.

The Paleozoic group of rocks in the interior of the Mississippi Basin measures only a few thousand feet in thickness, and limestones are there relatively more abundant than clastic deposits, because of the generally greater distance from the eroding lands.

In the western United States, Paleozoic strata usually show a thickness of many thousands of feet, and limestones are there also prominently developed.

The only large masses of igneous rocks of Paleozoic age are listed beyond under the caption "Igneous Activity."

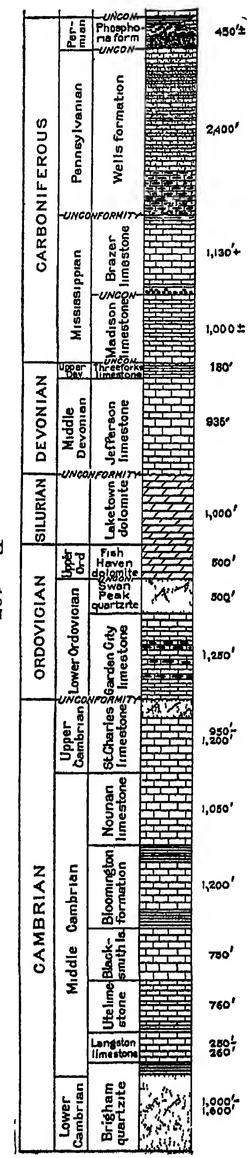


Fig 137 Columnar section showing the character and thickness of the formations, representing all of the seven periods of the Paleozoic, in southeastern Idaho. This area, in the great Cordilleran geosyncline, was submerged during nearly all of the larger North American marine floods Note the predominance of limestone. The total thickness of the formations is over 15,000 feet (After G. R Mansfield, U. S. Geological Survey)

Physical History

Relations of Land and Sea. — During Paleozoic time the most persistent, large, land areas (so-called "positive elements") which tended to stand out above the various epicontinental seas were as follows: *Appalachia*, which extended eastward from the Appalachian region to the deeper part of the Atlantic Ocean; *Canadia*, which covered much of northeastern Canada and Greenland; *Cascadia*, which extended from

northern California to Alaska; and *Mexicoia*, which covered the general region of Mexico.

Lying between the four lands just mentioned, were the wide areas which tended to be flooded repeatedly (so-called "negative elements"). The Appalachian and Cordilleran geosynclines, in the

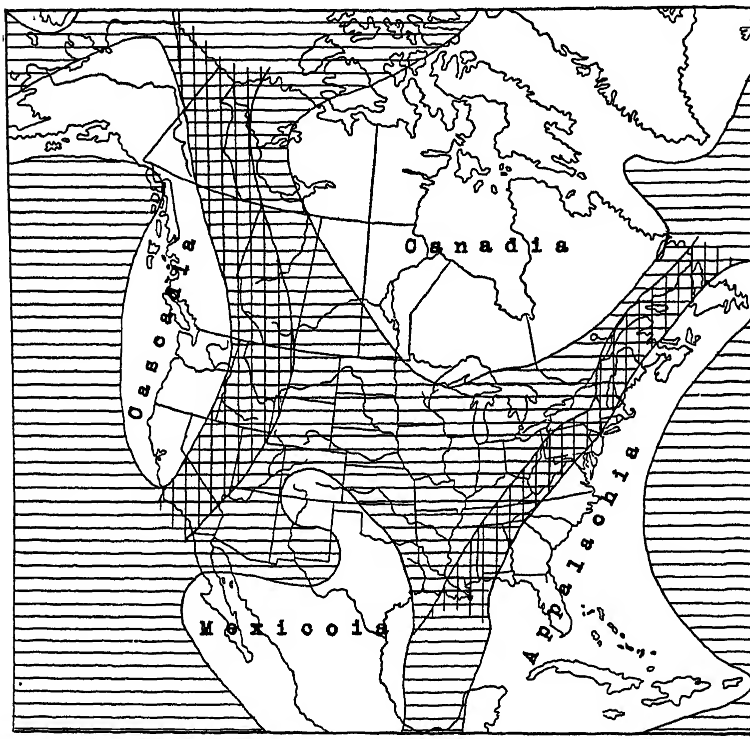


Fig. 138

Highly generalized paleogeographic map of North America from Cambrian to Mississippian time, inclusive. White areas, more persistent lands (positive elements); ruled areas, more persistent seas (negative elements); cross-ruled areas, Appalachian and Cordilleran geosynclines (Principal data, modified by the author, from maps by B. Willis and C Schuchert)

eastern and western parts of the continent, respectively, were the most persistent and well-defined portions of the negative areas (Fig. 138).

There were many oscillations of level between land and sea, causing repeated emergence and submergence of large and small areas, varying from a condition of the continent wholly land to fully two-thirds flooded Generally considered, the Paleozoic lands were relatively low and featureless — very different from the lands of today — and the epicontinental seas were shallow. There were, of course, more or less locally and at various times, considerable elevations of the land.

In this brief summary only certain very important geographic changes will be mentioned. The accompanying generalized map (Fig. 138) should be studied, and the paleogeographic maps should be reviewed.

The era opened with North America a land area. Early in the Cambrian, marine waters, in the form of long sounds, extended through the Appalachian and the Cordilleran regions. In the later Cambrian at least one-third of the continent was under water, but at the close of the period all was land.

There were three great marine invasions during the Ordovician, most extensive of all in the middle of the period when fully two-thirds of the continent was submerged.

Beginning with the continent all land, the Silurian was marked by several important marine transgressions, the one in the middle of the period having covered fully one-half of the continent. Very little sea water remained at the close of the period.

An outstanding feature of the Devonian was a more or less steady advance of the sea from the beginning of the period to a little beyond its middle when nearly one-half of the continent was submerged. A general withdrawal of the sea left all dry land at the close of the period.

About one-third of North America became submerged during earlier Mississippian time, followed by considerable retrogression of the sea in the midst of the period. Another extensive submergence marked later Mississippian time. All was land at the close of the period.

A great feature of Pennsylvanian time was a more or less progressive submergence of a considerable portion of the continent, beginning in the east and spreading westward across the United States, and thence northward into Alaska. The great coal-forming swamps of the east were important.

The Late Pennsylvanian sea continued into the earliest Per-

mian, after which there was a more or less steady retrogression of the sea, first from the eastern, and then from the western, part of the continent, leaving all dry land before the close of the period.

Mountain-making. — During the Paleozoic era there were four important movements in North America when rocks were folded into mountain ranges. The first was the Taconic Revolution at the end of the Ordovician when part of the eastern border of the continent was considerably folded and elevated. The second was the Acadian Revolution, which orogeny affected eastern New England and New Brunswick at the close of the Devonian. The third was the Ouachita Revolution in Oklahoma and Arkansas, near the close of the Mississippian. The fourth was the Appalachian Revolution, by far the grandest of all, when the whole Appalachian region from Alabama to the Gulf of St. Lawrence was greatly folded.

It is a significant fact that all of these important orogenic disturbances occurred within the southeastern one-fourth of the continent, this being in marked contrast with the great mountain-making disturbances of Mesozoic and Cenozoic times in western North America.

Igneous Activity. — The long Paleozoic era was, until near its close, relatively free from important igneous activity in North America. An extensive Ordovician ash bed in the southern states; several thousand feet of volcanic rocks in the Silurian of Maine and New Brunswick; some Devonian lavas in northern California, and in the New England-New Brunswick region; some volcanic rocks of Mississippian age in Nova Scotia and New Brunswick; and large bodies of volcanic rocks in the Pennsylvanian from California to Alaska, constitute the principal known records of Paleozoic volcanic activity.

The only important plutonic igneous intrusions of Paleozoic age in North America seem to have been the considerable invasions of granite magma which accompanied the Acadian Revolution, and the great granite invasions which accompanied the Appalachian Revolution.

In Europe igneous activity was more frequent and widespread.

Climate

The strongest evidence from the character and distribution of the organisms points to a temperate and rather uniform climate for most part over the globe during Paleozoic time.

Typical glacial deposits show that extensive areas were glaciated about the beginning of the early Cambrian and again toward the close of the era (Permian).

Certain deposits such as the "Red Beds," salt, and gypsum indicate at least local arid climate conditions, as for example in northern Siberia (Ordovician); New York (Salina epoch of the Silurian); Michigan, Montana, Nova Scotia, and Australia (Mississippian); and southwestern United States, western and central Europe, and other parts of the world (Permian).

Organic History

Viewed in a broad way, the life of the Paleozoic is distinctly different from that of the succeeding Mesozoic or Cenozoic. Very few species and not many genera passed from the Paleozoic to the Mesozoic, and even the larger groups of organisms which did continue usually underwent important structural changes. Paleozoic organisms were the more primitive in structure, and it has been aptly said that they bear somewhat the same relation to the succeeding forms that the embryo does to the adult.

Of plants in the early Paleozoic only the simplest Cryptogams are known, while in the later Paleozoic periods there are abundant records of the higher Cryptogams such as Lycopods, Equisetæ, and Ferns, as well as of the Gymnosperms. Angiosperms (typical flowering plants) are wholly unknown from the Paleozoic, and even the later forests and foliage of the era must have presented a gloomy appearance because of the lack of true flowering plants as compared with today.

The animals of the Paleozoic were predominantly invertebrates, though Fishes were common in the Devonian and later periods, and Amphibians and Reptiles appeared in the later periods. Among the most common and characteristic types of invertebrates were Graptolites, Corals, stalked Echinoderms (Pelmatozoans), Bryosoans, Brachiopods, Tetrabranch Cephalopods (Nautiloids especially), Trilobites, and Eurypterids. Certain of the higher Arthropods such as Spiders, Myriapods (Centipedes), and Insects did not appear till the era was rather well advanced.

The accompanying chart has been devised by the writer for the purpose of bringing together the salient facts in the organic history of the Paleozoic era. Period by period the principal evolutionary changes in the sub-kingdoms and classes of organisms are shown.

TABULAR SUMMARY OF PALEOZOIC LIFE

	Plants	*Protozoans*	*Porifers and Cœlenterates*	*Echinoderms*
PERMIAN	Thallophytes Bryophytes Pteridophytes Lycopods reduced, Equisetæ and Ferns common (Seed-ferns) Gymnosperms Common, e g Cycads, Cordaites, Conifers	Foraminifers Very common Radiolarians Present	Sponges Present Corals Ancient Tetracoralla still common, but first Hexacoralla appear	Crinoids Greatly diminished Asterozoans Present. Echinoids Present
PENNSYLVANIAN	Thallophytes Bryophytes Pteridophytes. Culminate, e g Lycopods, Equisetae and Ferns (Seed-ferns) Gymnosperms Simple ones common e g Cordaites	Foraminifers Very abundant Radiolarians Present	Sponges Present Corals Similar to Mississippian but less common	Blastoids Become extinct Crinoids Declining Asterozoans Present Echinoids Rare
MISSISSIPPIAN	Thallophytes Bryophytes Pteridophytes Common and much like Devonian (Seed-ferns) Gymnosperms Simple types only present	Foraminifers Very abundant Radiolarians Common	Sponges Common Graptolites Very rare and become extinct Corals Cup and Honey-comb forms only, and less prominent than in the Devonian	Blastoids Culminate and become nearly extinct Crinoids Culminate in numbers and species Asterozoans: Not common Echinoids Common.
DEVONIAN	Thallophytes Sea-weeds and Diatoms Bryophytes? Pteridophytes: Lycopods, Equisetæ, and Ferns (Seed-ferns) Gymnosperms Simple types only	Foraminifers. Present Radiolarians Present	Sponges Common Graptolites Decline almost to extinction Corals Cup and Honey-comb forms greatly increased in numbers and size, Chain corals rare and become extinct	Cystoids Rare and become extinct Blastoids Still uncommon Crinoids Still increasing Asterozoans. Abundant Echinoids Present
SILURIAN	Thallophytes Sea-weeds Bryophytes? Pteridophytes Ferns, but rare	Foraminifers. Present Radiolarians Present	Sponges Common Graptolites Diminished in numbers and species Corals Increase in prominence and Chain-corals attain their climax	Cystoids Prominent Blastoids Still rare Crinoids Increase in numbers and species. Asterozoans and Echinoids Increase
ORDOVICIAN	Thallophytes Sea-weeds Higher Cryptogams?	Foraminifers Abundant Radiolarians: Abundant	Sponges Very common Graptolites: Reach climax in numbers and species. Corals Common e g Cup, Honey-comb, and Chain forms	Cystoids Culminate Blastoids. First appear and rare Crinoids First appear and common. Asterozoans and Echinoids First appear and rare
CAMBRIAN	Thallophytes. Algæ	Foraminifers. Present	Sponges Common Hydrozoans. Graptolites and Jelly-fishes, both common Corals Present?	Cystoids Primitive forms and rare.

TABULAR SUMMARY OF PALEOZOIC LIFE — *Continued*

Molluscoids	*Mollusks*	*Arthropods*	*Vertebrates*
Bryozoans Abundant. Brachiopods Still common, with new species, straight-hinged forms still prevail	Pelecypods Greatly increased in numbers and species Gastropods Common Cephalopods Some earlier forms still persist, but Ammonoids (e g Waagenoceras) now common and more complex	Trilobites Very rare and become extinct Eurypterids Become extinct Insects Much like the Pennsylvanian	Fishes and Amphibians Much like the Pennsylvanian, but with new species Reptiles Many representatives of the lower orders
Bryozoans Common Brachiopods Still declining, but fairly common, straight-hinged forms prevail.	Pelecypods Still increasing Gastropods Common and first land forms appear Cephalopods Similar to Mississippian, but Nautiloids declining and Ammonoids more complex	Trilobites Rare Eucrustaceans Present Arachnids Eurypterids still declining, first Spiders appear Myriapods Common Insects Common and large, simpler types only	Fishes Much like Mississippian. Amphibians Culminate, e g Stegocephalans Reptiles Present?
Bryozoans More abundant than in the Devonian Brachiopods Declining but still common and with many new species, mostly straight-hinged forms	Pelecypods More common than before Gastropods Common Cephalopods Much like the Devonian, but coiled Nautiloids culminate and Ammonoids are more complex	Trilobites Rare Eucrustaceans? Arachnids Eurypterids declining Myriapods Present Insects. No fossils.	Fishes Selachians increasing, Dipnoans declining, Arthrodirans declining, Ganoids increasing Amphibians Present.
Bryozoans Present Brachiopods Culminate in numbers and species, many new forms added, mostly straight-hinged forms	Pelecypods and Gastropods Much like the Silurian Cephalopods Most earlier forms persist, but Ammonoids first appear, e g Goniatite.	Trilobites Decline markedly Eucrustaceans, Common Arachnids. Eurypterids declining, but still notable for size Myriapods First known Insects Unknown	Ostracoderms. Culminate and become extinct Fishes Very profuse, e g Selachians, Dipnoans, Arthrodirans and Ganoids Amphibians?
Bryozoans. Abundant Brachiopods Prominent in numbers and species, nearly all straight-hinged forms	Pelecypods and Gastropods Common and much like Ordovician Cephalopods Common and much like Ordovician, but coiled Nautiloids predominate	Trilobites Diminished but still common Eucrustaceans Similar to Ordovician Arachnids First Scorpions, Eurypterids culminate in numbers, species and size (?)	Ostracoderms Rare, small and primitive. Fishes Selachians of primitive character and rare
Bryozoans. Abundant Brachiopods More complex, larger, and abundant; Articulates prevail; and nearly all are straight-hinged forms	Pelecypods Larger and more common Gastropods· Common Cephalopods Very prominent and all are Nautiloids, e.g Orthoceras, Cyrtoceras, Trochoceras and Trocholites	Trilobites Culminate in numbers and species Eucrustaceans. Few and simple Eurypterids. Present	Ostracoderms Marking first appearance of Vertebrates, specimens rare and very fragmentary
Bryozoans Absent Brachiopods Small, thin-shelled; Inarticulates prevail, some Articulates in the Upper Cambrian	Pelecypods· Very small and rare Gastropods Rare, simple and mostly in the Upper Cambrian Cephalopods Rare, small and simple; all Nautiloids e g, Orthoceras and Cyrtoceras	Crustaceans. Trilobites common and usually highly segmented and with small tail plates, some very simple forms Eurypterids Rare	None

"A study of the Paleozoic faunas of North America shows that they were derived from three permanent oceanic realms. According to Schuchert, these were, in their order of persistence, the Gulf of Mexico mediterranean, which in reality is but the southern part of the northern Atlantic; the Pacific; and the Arctic. The faunas of the northern part of the north Atlantic were as a rule confined to the northeastern part of North America, though at times they spread into the interior basin. Pacific faunas at times spread completely across the continent to the foot of Appalachia. Arctic waters pulsated southward along the middle region of the continent far into the United States during the Ordovician and Silurian periods, and less positively at other times. Faunas from the Gulf of Mexico frequently spread far throughout the Mississippi Valley and Appalachian areas. They were at times also tinged with south European or South American forms." [1]

It seems to be a well established fact that profound changes in the natural environment have produced fundamental changes in the plant and animal realms. Thus the late Paleozoic and early Mesozoic was a time of one of the most profound and far-reaching physical disturbances in the known history of the earth. Great mountains were being made in many parts of the world, particularly in eastern North America and in Europe; the lands were much increased in size and height; one of the two greatest known Ice Ages was a feature of the Permian; and the ocean waters were affected in various ways. These physical changes in turn caused climatic changes, altered habitats of plants and animals, and modified sources of food for the animals. Accompanying these changes, the giant Lycopods, Seed-ferns, and Cordaites became extinct, while higher plants, such as Cycads and Conifers, began to clothe the earth. Large groups of animals, such as Tetracoralla, Blastoids, Orthoceras, Trilobites, and Eurypterids disappeared from the waters; Amphibians culminated; and Hexacoralla, Insects, Reptiles, and Mammals made their appearance.

It is a very significant fact, from the standpoint of evolution of life on the planet, that very few if any species of either plants or animals of Paleozoic time have continued to exist to the present day. In other words, since the Paleozoic era closed, all life, in regard to its myriads of species, has undergone a practically complete revolution.

[1] G. R. Mansfield. U S. G S, *Prof. Paper* 152, 1927, p. 177.

THE MESOZOIC ERA

CHAPTER XIV

THE TRIASSIC PERIOD

Origin of Name, Subdivisions, Etc.

The name "Triassic" was given because of the threefold, extensive development of the rocks of the system where first studied in Germany. It so happens, however, that the German Triassic strata are not typical of the system, as shown by later studies in other parts of the world.

The following table gives a general idea of the main subdivisions in North America and Europe:

	Europe	*California*	*Colorado Plateau*	*Massachusetts*
Upper Triassic	Keuper: Rhætic Noric Karnic	Swearinger (Shale) Hosselkus (Limestone)	Chinle (Sandstone and shale) Shinarump (Conglomerate)	Newark (Conglomerate, sandstone, and shale)
Middle Triassic	Muschelkalk	Pit (Shale)	?	(Missing)
Lower Triassic	Bunter	Shale in Inyo Mts	Moenkopi (Shale and sandstone)	(Missing)

Distribution and Character of the Rocks

General Distribution. — The accompanying map (Fig. 139) shows the surface distribution of both the Triassic and Jurassic rocks in North America. The Atlantic Coast areas are wholly Triassic; the California areas are mainly Jurassic; and the remain-

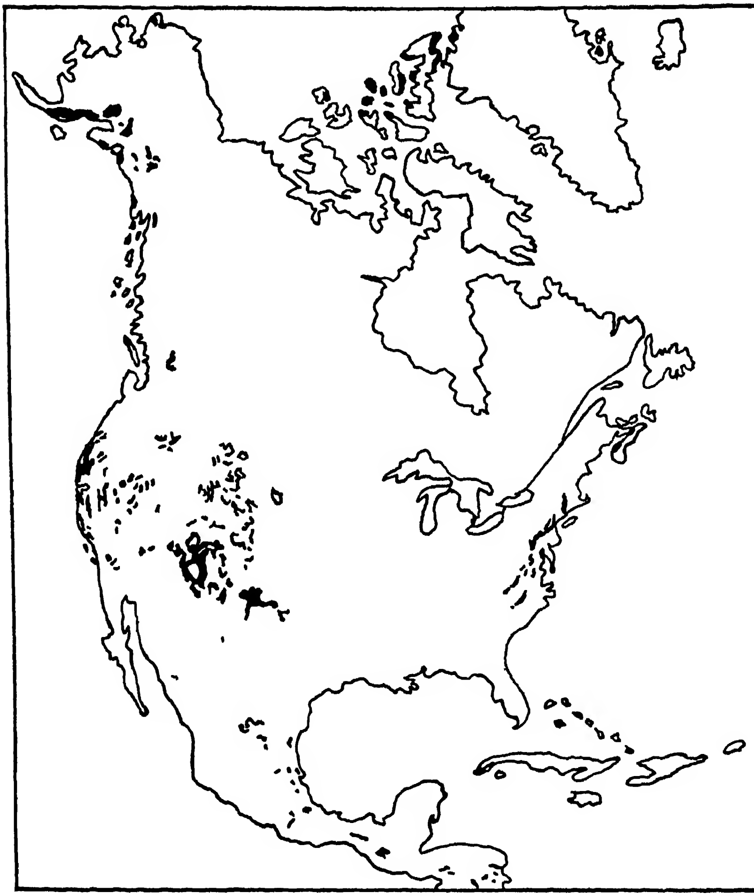


Fig 139

Map showing the surface distribution (areas of outcrops) of Triassic and Jurassic strata in North America Some areas of doubtful age and extent not shown in British Columbia. All Atlantic Coast areas are Triassic. In much of the western United States the Triassic and Jurassic have not yet been satisfactorily separated. (By W J M., data from two maps by Bailey Willis, U. S. Geological Survey.)

ing areas include both Triassic and Jurassic rocks which have usually not been carefully separated. There is no reason whatever to believe that Triassic rocks were ever deposited over Canada except along the western coast and to a slight extent in Nova Scotia. Likewise it is not known that Triassic rocks ever occurred in the Mississippi Basin except immediately east of the Rocky Mountains. This is in marked contrast with the Paleozoic systems. Accordingly, the present concealed Triassic rocks and areas of their former presence are largely confined to the regions of existing outcrops.

Rocks of the Atlantic Coast.—These rocks (Newark series) are seen on the map to occupy comparatively small, narrow areas just east of and parallel to the Appalachian Mountain range from southeastern New York to South Carolina, and farther northward in the Connecticut River Valley and in Nova Scotia. In the northern areas the rocks are sandstones and shales, with some coarse conglomerates, especially at the base. Because of their prevailing red color and general resemblances to the "Old Red Sandstone" (Devonian) of Scotland, they have been called the "New Red Sandstone." Many of the beds show suncracks, raindrop pits, ripple-marks, and footprints, and remains of land Reptiles (Dinosaurs). In Virginia and the Carolinas the rocks have a similar lithologic character, though the red color is not so common, and some workable coal beds occur. The fossils, which are mostly plants in the dark shales, point to the Upper Triassic age of the Newark series.

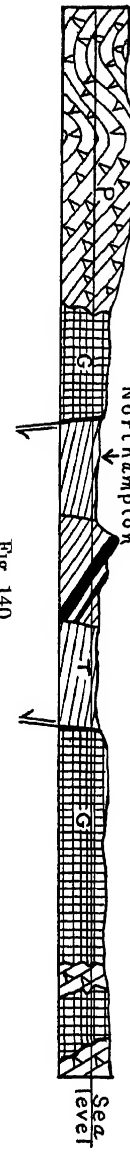


Fig. 140

Structure section across the Triassic Basin of the Connecticut Valley near Northampton, Massachusetts, showing the tilted and faulted character of the rocks Strike of the section, northwest Length of section, about 40 miles *P* = Paleozoic schist; *G* = late Paleozoic granite, *T* = Triassic strata, with sheets of lava (black layers). (From the author's "Geological History of the Connecticut Valley of Massachusetts.")

The rocks of the series are nearly everywhere somewhat folded, tilted, and extensively fractured by normal faults, and they also contain numerous lava flows, intrusive sheets, and dikes of so-called trap rock (diabase) (Figs. 140, 141). A remarkable feature is the great thickness of the rocks in these narrow belts, fully 3000 feet in Virginia; 7000 to 10,000 feet in the Connecticut Valley and 10,000 to 15,000 feet in New Jersey.

Rocks of the Western Interior. — The Triassic strata of the western interior region are distributed over nearly the same areas

Fig 141

Tilted Triassic shale and sandstone in the Connecticut Valley, near Holyoke, Massachusetts. (Photo by the author)

as the Permian, and in many places the rocks of these two systems are not at all sharply separated. All the known Triassic rocks of the western interior of the United States are located within the cross-lined area on map Fig. 144. They are much like the Permian of this region, but they are even more typical of the so-called "Red Beds." Sandstone and shale, with some conglomerate, limestone, and gypsum, are the predominant rocks. Some of these rocks are of restricted marine origin, but most of them are of either salt-lagoon or terrestrial origin. Their thickness varies from a few

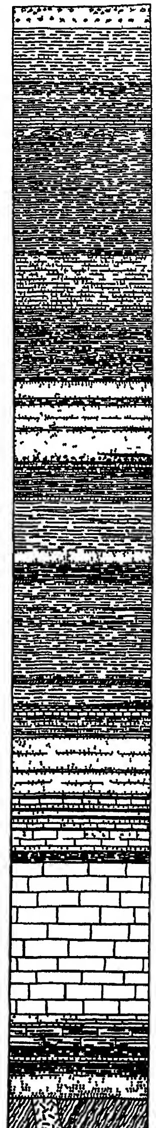
System	Kind of Rock	Columnar Section	Thickness in Feet
Oligocene	sand and gravel		25–150
Cretaceous	gray shale limestone dark shale and sandy-shale		1390
	red and buff sandstone gray and buff shale		325–590
Jurassic	red and buff sandstone and shale		325
Triassic	red shale and gypsum		500+
Permian	limestone and red sands		100–120
Pennsylvanian	white sandstone gray to red limy sandstone		500+
Mississippian	red shale gray limestone		650
Ordovician	pink limestone		80
Cambrian	shale sandstone		100–300
Pre-Cambrian	schist, granite		

Fig. 142

Columnar (geologic) section showing ages, character and thickness of strata in northeastern Wyoming. Note the prevalence of red-beds toward the middle of the section. (After Darton, U. S. Geological Survey, Folio 127.)

hundred feet in the eastern part of the western interior to 2500 feet or more in Utah and Arizona. The Triassic strata are locally much folded in the mountains, but over wide areas they are nearly horizontal.

Triassic rocks are wonderfully and widely exposed in the Colorado Plateau where the nearly horizontal strata lie from 5000 to 10,000 feet above sea level. Because of their high degree of sculpturing and coloring, as in the Painted Desert of Arizona,

Fig 143

Steep-dipping Triassic shale and limestone (bold outcrops) in the Inyo Mountains, near Keeler, California. (Photo by A R Whitman)

they form a striking feature of the landscape. The Triassic formations of the Colorado Plateau (see preceding table) are a variable assemblage of shale, sandstone, conglomerate, limestone, and gypsum, reaching a total thickness of 2000 to 3000 feet. Petrified wood is abundant, as in the Petrified Forest of Arizona.

Rocks of the Pacific Coast.—These include the only true marine Triassic rocks of North America, and they are there exten-

sively developed with practically all portions of the system from oldest to youngest well represented, particularly in California and Nevada. The rocks consist mostly of shales, slates, limestones, conglomerates, and sandstones, usually several thousand feet thick with a maximum thickness of 13,000 feet in British Columbia.

In California, southern Alaska, and British Columbia the system contains great quantities of igneous material, mainly lavas and tuffs.

In central-eastern California (Inyo Mountains) Lower and Middle Triassic shales and limestones 1500 feet thick are overlain by Upper Triassic shales and tuffs 5000 feet thick. In northern California the Lower Triassic seems to be missing, but Middle Triassic shale and Upper Triassic limestone and shale reach a thickness of several thousand feet.

In southeastern Idaho, Lower Triassic only occurs and this consists of several thousand feet of shale, limestone, and sandstone.

Thickness of the System and Igneous Rocks. — Figures showing the thickness of the system in different parts of the continent have already been given. Volcanic rocks are abundant in the Triassic of British Columbia, southern Alaska, California, and also in the Newark series of the Atlantic Coast, the last named being again referred to below. In British Columbia Triassic lavas and volcanic ashes are often several thousand feet thick, reaching a maximum of possibly 10,000 feet.

Physical History

Atlantic Coast. *Basins of Deposition.* — Accompanying map Fig. 144 shows the areas of continental deposition in eastern North America during Upper Triassic time. These were all in the general Appalachian region. The non-marine formations (Newark series) of Upper Triassic age clearly show by their distribution and mode of occurrence that they were deposited in a series of long, troughlike basins. Because these troughs were situated between two great land masses — Appalachia and the newly formed Appalachians — the conditions were very favorable for rapid accumulation of thick deposits in them. The great thickness of the strata (maximum, 2 miles or more) strongly points to a subsidence of the basin floors while the deposition was in progress. Most of the

rocks are well stratified. The generally red color and freshness of the material in the formations indicate that the climate of the time was arid or semi-arid, and the presence of sun-cracks, ripple-marks, and tracks of land animals at many horizons show that

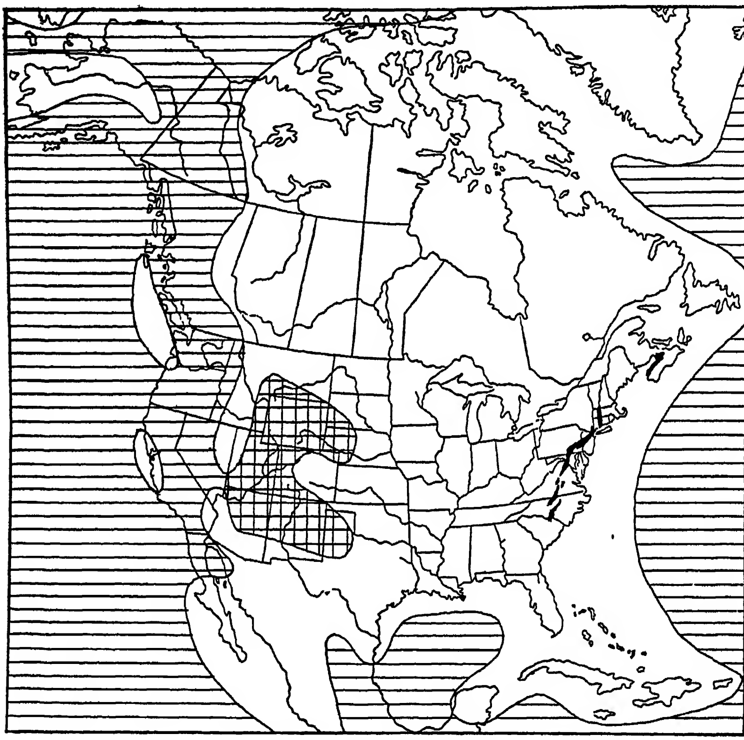


Fig. 144

Paleogeographic map of North America during Late Triassic time White areas, land; ruled areas, sea; cross-ruled areas, partly marine and partly continental; black areas, continental deposition (Principal data, modified by the author, from maps by B. Willis, C Schuchert, and E B. Branson)

the beds were laid down in part on land, but mostly under shallow water, such as flood-plains and playa lakes, where frequently changing conditions often allowed the surface layers to lie exposed to the sun. The Newark series generally consists of three

formations — a very coarse conglomerate and conglomeratic sandstone upon which lie in turn sandstone and shale formations.

A conception of the origin and filling of the Triassic basins may be gained from the following statements which were written in regard to the Connecticut Valley of Massachusetts. By the opening of Late Triassic time the great, new mountains of eastern North America had been considerably reduced by erosion. Then a sinking of the basin area began. "At first the sinking of the basin floor was probably a slow down-warping process such as is known to have taken place in many districts during geological time. This original down-bending of the Triassic Basin is best explained as a continuation (or renewal) of the Appalachian Mountain folding, this view being supported by the fact that all of the Triassic basins of sedimentation from Nova Scotia to North Carolina follow exactly the trend of the Appalachian folds. As the trough sank the adjacent lands were rejuvenated by elevation. Streams entering the basin from the growing highlands were renewed in activity, and they carried loads of coarse material which accumulated on the floor of the low-level basin. The load of accumulating sediments probably aided or accentuated the down-bending process "[1] The great thickness of the very coarse materials, especially along the sides of the basin, leads to the conclusion that the margins of the basin must have been high and very steep during the whole time of the deposition of these materials, else the streams would not have been swift enough to transport the coarse debris. Such very steep valley-sides could not, however, have resulted from simple down-warping. More than likely, therefore, normal faults developed on the sides of the subsiding, filling basin, and the subsidence was then largely a more or less intermittent sinking of the fault-block. The present-day structure of the valley is that of a sunken fault-block made up of minor tilted blocks (Fig. 140).

Footprints of Reptiles. — Remarkable Reptiles of Triassic time, known as Dinosaurs, left numerous footprints on exposed mud-flats in various places. In many cases the tracked surfaces, after drying in the sun, were covered by the deposits left by succeeding flood waters. Such tracks are found here and there through thousands of feet of strata, particularly in the Connecti-

[1] W. J. Miller: *Geological History of the Connecticut Valley of Massachusetts,* 1921, pp. 36–37.

cut Valley. Outcrops of these footprint-bearing strata are fine illustrations of the remarkable detail in which some geological records may be preserved. An excellent outcrop, about 30 by 150 feet in size, may be seen close to the road a few miles north of Holyoke, Massachusetts. Dozens of tracks, made by several sizes and species of two-legged Dinosaurs, may be seen in an amazing state of perfection on the surface of this ledge. The tracks, which are three-toed, range in length from 3 to 16 inches (Figs. 152, 153). Ripple-marks, and even raindrop impressions, also occur.

Volcanic Activity. — During the time of the formation of the Newark beds, there was considerable igneous activity, as shown by the occurrence of sheets of igneous rocks within the mass of sediments. In some cases true lava flows with cindery tops were poured out on the surface and then became buried under later sediments, while in other cases the sheets of molten rock were forced up either between the strata or obliquely through them, thus proving their intrusive character. As a result of subsequent erosion, these igneous rock masses often stand out conspicuously as topographic features. Perhaps the most noteworthy of these is the great igneous rock sheet, part of which outcrops to form the Palisades of the Hudson River, and which altogether outcrops for a distance of 70 miles. The molten rock first broke through the strata and then crowded its way along parallel to them. Another fine example is the so-called Holyoke Range of Massachusetts (Fig. 145) regarding which Emerson says: "The accumulation of sediments was interrupted by an eruption of lava through a fissure in the earth's crust, which opened along the bottom of the basin. The lava flowed east and west on the bottom of the bay, as tar oozes and spreads from a crack, and solidified in a sheet which may have been 2 or 3 miles wide and about 400 feet thick in its central part. This is the main sheet or Holyoke diabase."[1] In both regions just mentioned, the contraction of the cooling masses often expressed itself by breaking the rock into great and small, crude, nearly vertical columns, and hence the application of the term "palisades." The steep mountain sides or cliffs are due to the fact that the hard igneous rock is much more resistant to weathering and erosion than the sandstone above and below it (Fig. 145).

Western Interior. — In Early Triassic time the Pacific waters spread eastward in the form of a wide gulf over much of Nevada

[1] B. K. Emerson: U. S. G. S., *Holyoke Folio No. 50*, p. 3.

and to the western border of South Dakota and the northwestern corner of New Mexico. During most of the Middle Triassic, Nevada was still submerged under the sea, but the rest of the western interior was land, probably receiving continental deposits here and there. Late Triassic time was marked by the development of a great basin covering a large part of the western interior region. This basin seems to have been a more or less cut off arm of the sea, connected with the Pacific across southern Nevada

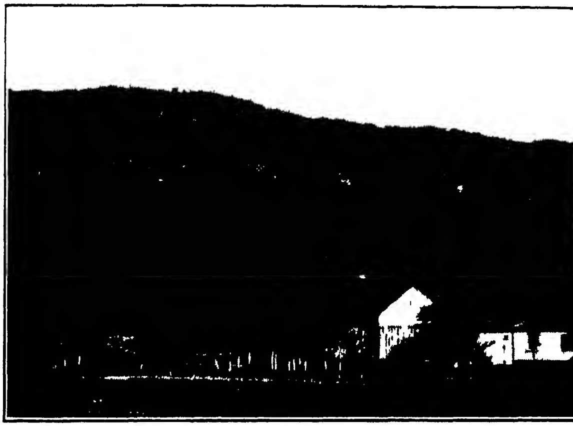


Fig 145

The steep western front of the Holyoke Range as seen from Easthampton, Massachusetts The upper portion is columnar lava of Triassic age, and this rests upon Triassic red sandstone (Photo by the author)

(see Fig. 144). Very typical Red Beds, indicating aridity of climate, were extensively developed in this basin. Modified marine, great salt lagoon, salt lake, and even terrestrial conditions seem to have prevailed from time to time in this basin.

Pacific Coast. — Viewed broadly, there was a progressive submergence of much of the Pacific Coast of North America during Triassic time. Early in the period most of California and Nevada were submerged under the sea; in the middle of the period there was added a wide embayment over much of British Columbia and the southern end of Alaska; and in the Upper Triassic almost the whole Pacific Coast area from central Lower California to south-

western Alaska was under the sea. There was probably also a connection with the Arctic Ocean across eastern Alaska. Map Fig. 144 shows the extent of the greatest North American Triassic sea.

In eastern and northern California, western British Columbia, and southern Alaska submarine volcanic activity took place on a tremendous scale in later Triassic time as proved by the direct association of thousands of feet of lavas and tuffs with marine strata.

Close of the Triassic. — The Triassic closed in eastern North America with crustal disturbances which raised the basins of deposition of the Newark series into dry land, and broke the strata, and associated lavas and intrusive sheets, into a great series of tilted fault-blocks, thus leaving all of the eastern half or two-thirds of the continent dry land and undergoing erosion.

In the western interior the geographic conditions toward the close of the Triassic are as yet more doubtful because scarcity of fossils renders a separation of possible Jurassic strata from Triassic uncertain. The best evidence, however, points to continual deposition of "Red Beds" over much of the region.

There seems to be clear evidence that marine waters withdrew from the Pacific Coast region during latest Triassic time.

Foreign Triassic

Europe. — As in America, so in Europe, the Triassic shows considerable development of both continental and marine facies. The Bunter series (1600 to 1800 feet thick) of Germany consists chiefly of red beds, such as sandstones and shales, with some salt and gypsum, clearly indicating deposition under arid climate conditions much like the western interior of the United States at the same time. The Muschelkalk of Germany is mostly a marine limestone formation up to 1000 feet thick, thus showing the presence of marine waters over the region, probably as an arm of the sea, similar to the Baltic Sea, as the fossils suggest. During part of this time, at least, salt lake conditions were restored as indicated by gypsum and salt in the midst of the series. During Keuper time conditions of deposition were much as during the Bunter, though marine waters again transgressed the area toward the close of the Triassic.

In England, much of eastern Russia, and western and southern

Spain, Triassic strata essentially like those of Germany are well developed.

In middle southern Europe the marine facies is widely developed, being mostly limestone (often dolomitic) and shales. The rugged peaks of the famous "Dolomites" or Tyrolean Alps have

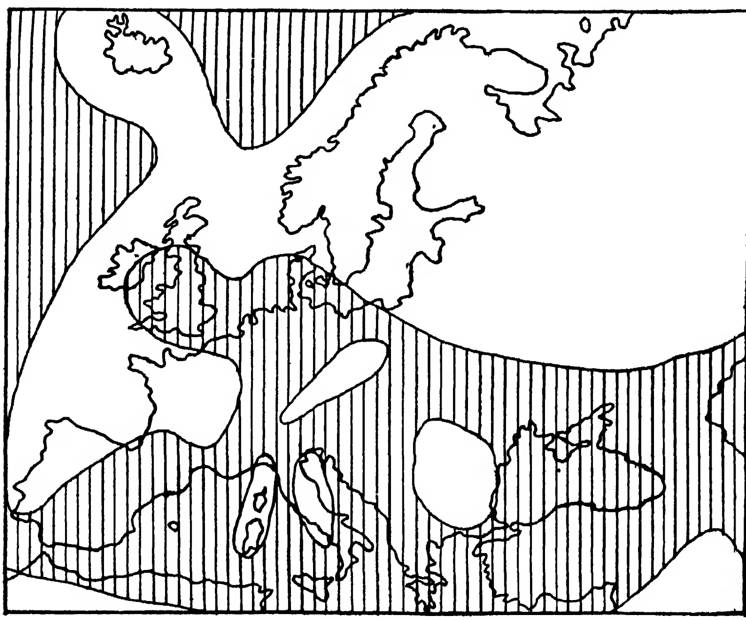


Fig. 146

Sketch map showing the relations of land and water in Europe during Upper Triassic time. White areas, land; ruled areas, sea (Modified by the author after F X Schaffer)

been carved out of this comparatively resistant dolomitic limestone, much of which was of Coral-reef origin.

Map Fig. 146 gives a good idea of the relations of land and water in Europe during Late Triassic time.

Other Continents. — The marine facies of the European Triassic continues eastward through much of southern Asia, there being an unusually fine development of the system in the Hima-

layas. Triassic rocks, sometimes of continental origin, also occur in other parts of Asia as in Japan and eastern Siberia.

Triassic rocks are also known in Australia, New Zealand, north and south Africa, and South America, with coal-bearing strata in Argentina and Chile, and marine strata in the Andes.

Climate

The extensive areas of "Red Beds," often accompanied by salt and gypsum, in the western interior and eastern North America, northern and western Europe, and northern Africa show widespread aridity of climate in the northern hemisphere during the period. There is no evidence of glaciation, and the fossils indicate general mildness of climate, except at the close of the period when the temperature was distinctly lower than usual. Judging by the character and distribution of the fossils, the water of the Arctic Sea was appreciably cooler than that of lower latitudes, so that climatic zones must have been defined to some extent at least.

Economic Products

Coal beds of some commercial value occur in the Triassic rocks of Virginia and North Carolina.

Enormous quantities of sandstone (the so-called "Triassic Brownstone") for building purposes have been quarried from the Newark series, especially in the Connecticut River Valley.

Gypsum of Triassic age is quarried in some of the western states.

Some copper deposits occur in Triassic rocks of California and Alaska.

Life of the Triassic

The physical revolution which closed the Paleozoic era was accompanied by one of the most profound changes in organisms in the earth's history, and hence we may expect the life of the Triassic to have been very notably different from that of preceding time. Some types of animals and various types of plants continued from the late Paleozoic, but the general aspect of Triassic life was distinctly more modern than that of the Paleozoic. In spite of this comparatively rapid evolutionary change in both fauna and

flora, enough connecting links are known to make sure that the Mesozoic animals and plants were derived from the Paleozoic.

Plants. — Triassic plants have not left us a very abundant record. The rather widespread aridity of climate doubtless hindered a luxuriant growth, over wide areas at least.

Among the simple plants (*Thallophytes*) the calcareous *Sea-weeds*, that is those which had the power to secrete limy skeletons, were especially common.

Among *Pteridophytes* the *Ferns* and their allies were still important; the *Equisetæ* were fairly common, though much more like the existing forms except for their greater size; and the *Lycopods* were reduced almost to extinction, even the few lingering *Sigillarians* having finally disappeared with this period, so that the Lycopods will not again call for special mention.

Fig 147

Parts of a Triassic Conifer, *Voltzia heterophylla* (After Fraas from Scott's "Geology," courtesy of The Macmillan Company)

Gymnosperms were the dominant types of plants of the Triassic, just as Pteridophytes had been the dominant plants of the later Paleozoic. The *Cordaites* were greatly reduced and they became extinct during this period. *Cycads* and their allies and the *Conifers* (Fig. 147), however, were the most common larger elements of the flora. Fig. 160 gives a good idea of a modern Cycad, though it must be understood that such plants are today relatively unimportant in spite of the fact that more than a hundred species are known.

Not only because the Cycads of Mesozoic (especially Triassic and Jurassic) time were so profuse in numbers and in variety of species, but also because they were remarkably widespread over the earth, the Mesozoic era has sometimes been called the "Age of Cycads." Cycads varied much in size from small palmlike forms to trees 40 to 60 feet high and several feet in diameter. From the standpoint of evolution, it is important to note that much

Fig. 148

Sections of petrified tree-trunks weathered out of Triassic strata in the Petrified Forest of Arizona. (Photo by G. P Merrill, U. S National Museum)

evidence leads to the conclusion that the earlier Mesozoic Cycads were the progenitors of the highest of all classes of plants — the Angiosperms. The Conifers, in marked contrast to this history, have not given rise to any higher group of plants.

It is generally stated that the plants of the Triassic, except toward the close of the period, in both Europe and America presented a stunted or dwarfed appearance on account of unfavorable (chiefly climatic) environment. Such an impoverished condition of

Triassic plants was at least not universal, for as Knowlton says: "In North Carolina, Virginia, and Arizona there are trunks of trees preserved, some of which are 8 feet in diameter and at least 120 feet long, while hundreds are from 2 to 4 feet in diameter. Many of the Ferns are of large size, indicating luxuriant growth."[1]

The remarkably petrified trees found in such abundance and beauty in the Triassic strata of the Petrified Forest of Arizona represent mainly Conifers, which grew to be several feet in diameter and fully 150 feet high (Fig. 148).

Fig 149

A Triassic Ceratite, *Ceratites trojanus*, with part of shell removed to show suture structure. (After J P. Smith, slightly modified by accentuation of sutures)

Invertebrates. — Among the Corals, for the first time, the *Hexacoralla*, or forms of modern aspect, became abundant, while the ancient (Paleozoic) *Tetracoralla* dwindled away to extinction.

Crinoids were common, the more ancient types having given way to those of more modern aspect.

Echinoids (Sea-urchins) were common, though most of the dominant Paleozoic types were gone and all were forms of regular shape. For the first time the Echinoids were more prominent than the Crinoids.

Brachiopods showed two important changes, namely (1) a great reduction in number of species and of individuals, and (2) the shells with straight-hinge lines becoming subordinate to those with curved-hinge lines for the first time, a common genus (Terebratula) of the latter being represented by a Cretaceous form in Fig. 184. To the present day the Brachiopods never again became conspicuous elements of the fauna. In spite of the important changes, a few of the Paleozoic genera survived the transition to the Mesozoic.

Mollusks included the most abundant invertebrate animals of the period, all of the well-known classes having been prominently represented.

Pelecypods were more numerous and diversified than ever before. They vastly outnumbered the Brachiopod bivalves. Certain

[1] F. H. Knowlton: *Jour. Geol.*, Vol. 18, 1910, p. 106.

still existing genera were introduced so that many forms were of decided modern appearance.

Gastropods. Several Paleozoic genera existed for the last time, and certain more modern types appeared.

Cephalopods. Among the *Nautiloids* the straight-shelled form (Orthoceras), known from the very early Paleozoic, became extinct in the Triassic, while the coiled forms were still common and much like those of later Paleozoic time.

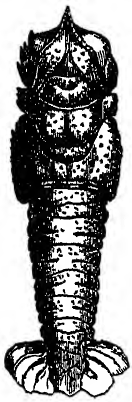


Fig 150

A Triassic long-tailed Macruran Decapod, *Pemphix Sueurii* (From Naumann)

Among the *Ammonoids* an evolutionary feature of particular interest was the development of still greater complexity of shell structure. Goniatite-like forms still persisted, but, even early in the Triassic, forms with slightly serrated sutures or partition structures (e.g. Ceratites, Fig. 149) appeared. Later in the period representatives of the most complex of all known chambered Cephalopods, that is the Ammonites, appeared (see Fig. 166).

Another important advance among the Cephalopods was the first appearance of the *Dibranchs*, which include the highest of all Mollusks. Of these Dibranchs perhaps the most characteristic belonged to a group known as *Belemnites* (see Fig. 169), though these were not abundant. A fuller discussion of the Dibranchs will be given in the next chapter.

Among *Crustaceans* neither *Trilobites* nor *Eurypterids*, so important in the Paleozoic, continued into the Mesozoic, but the *Eucrustaceans* showed a notable advance by the first appearance of the so-called long-tailed *Decapods* (*Macrura*) or Lobster family, which rank among the highest of all Crustaceans (Fig. 150).

Insects also showed distinct progress by the addition of the *Beetle* tribe, which ranks next to the highest of all insects.

Fishes. — *Selachians*, *Dipnoans*, and *Ganoids* (Fig. 151) all continued with the Ganoids predominant. Teleosts had not yet appeared.

Amphibians. — Though somewhat diminished as compared with the later Paleozoic, the Amphibians were still numerous and often notable for their great size. In general they were much like the

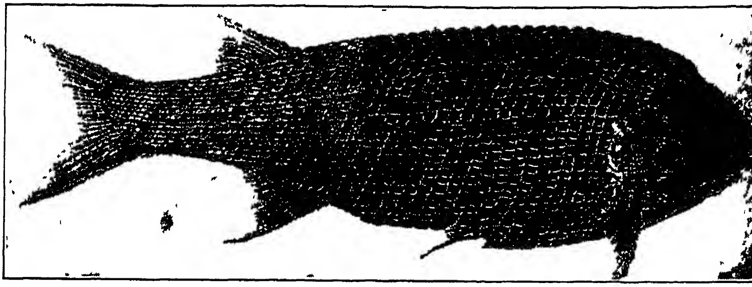


Fig 151

A Ganoid, *Catopterus redfieldi*, from the Triassic sandstone of Connecticut. (After Newberry, U S Geological Survey, Monograph 14)

late Paleozoic forms. *Mastodonsaurus* attained a length of 15 or 20 feet and had a skull 4 feet long. The Bunter series of Germany is particularly rich in fine fossil Amphibians. By the close of the

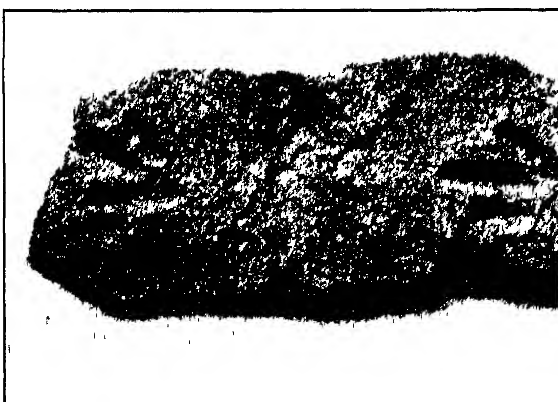


Fig 152

Tracks of a small two-legged Dinosaur on a slab of Triassic sandstone from the Connecticut Valley. The tracks are about 4 inches long. (Photo by the author)

Triassic the Amphibians had declined remarkably, so that among the land Vertebrates, of which they were the ancestors, they never again assumed a position of importance.

Fig 153

Tracks of a large two-legged Dinosaur on Triassic sandstone from the Connecticut Valley, showing how both feet slid some distance in the soft material after which the creature suddenly sat down, the end of the backbone having left a distinct impression. (After Edward Hitchcock.)

Reptiles. — Because of the great abundance, size, and variety of Reptiles, the Mesozoic era is often called the "Age of Reptiles." Even in the Triassic most of the more important and interesting now extinct groups had appeared, such as the swimming Reptiles (e g. *Enaliosaurs*); walking Reptiles (e.g. *Dinosaurs*; and flying Reptiles (e.g. *Pterosaurs*). Since these remarkable reptilian forms reached their climax of development later in the Mesozoic, a fuller

discussion will be reserved for a subsequent chapter. In passing, however, it may be mentioned that Dinosaurs, often of great size, were the creatures which left the numerous footprints up to 15 or 18 inches in length in the Newark sandstone of the Connecticut Valley (Figs. 152, 153).

Of the more modern reptilian forms, the *Turtles* and *Lizards* made their first appearance, the latter only in late Triassic time, but none of them became common.

Mammals. — Another very important step in the development of animal life was the introduction of Mammals in the Triassic period. Although Mammals include the most highly developed of all animals, their earliest representatives (in the Triassic) were very small, primitive types, apparently not very numerous, thus scarcely suggesting their later (Cenozoic) development into the manifold and most powerful and intelligent creatures of the earth. Only a few genera are known from the Triassic, and in fact Mammals continued to occupy a very subordinate position throughout the Mesozoic era.

According to Schuchert, "it is one of the most striking generalizations of Paleontology that the upwelling of future organic rulers begins in unobtrusive small forms. In all stocks of plants and animals such potential rulers are always present" This was distinctly true of the Fishes, Amphibians, Reptiles, and Mammals.

CHAPTER XV

THE JURASSIC PERIOD

ORIGIN OF NAME, SUBDIVISIONS, ETC.

THE rocks of Jurassic age are of peculiar interest because they comprise one of the very first systems whose subdivisions were carefully determined by the use of fossils, this work having been done in England about one hundred years ago by William Smith, who is often called the father of historical geology. Smith applied the name "Oolitic" to the system because of the common occurrence of so much oolitic limestone, but this term later gave way to the term "Jurassic," so called from the Jura Mountains, between France and Switzerland, where the rocks of the system are unusually well exhibited and have been much studied. In Germany, too, much study has been devoted to this system, largely because of the abundance of well-preserved and interesting fossils.

In western North America, where the only undoubted Jurassic strata occur on this continent, the subdivisions of the system are not so well known and correlated, so that various more or less local formation names are still employed The following table gives a summary of the principal subdivisions for four important regions.

DISTRIBUTION AND CHARACTER OF THE ROCKS

General Distribution. — Differing from all preceding systems, rocks of undoubted Jurassic age are wholly confined to the western part of the continent. On map Fig. 139 the considerable areas shown in California and western Nevada are mostly Jurassic rocks. Some areas are also definitely known in southern Alaska and in western Oregon. In the western interior numerous small areas of mostly Upper Jurassic rocks only are known from northern Arizona and northwestern Colorado northward through Idaho, Wyoming, western South Dakota, and Montana. Rocks of Upper Jurassic age also quite certainly occur in western British Columbia east of the Cascade Mountains.

As compared with all preceding systems since the early Paleozoic, rocks of the Jurassic system are the least extensively developed on the continent.

	Europe	*California*	*Rocky Mountains*	*Colorado Plateau*
UPPER JURASSIC	Malm	Mariposa (Slate). Foreman? Hinchman (Sandstone)	Morrison (Colored sandstone and shale) Preuss (Sandstone).	McElmo (Sandstone, shale, and gypsum).
MIDDLE JURASSIC	Dogger	Bicknell (Sandstone) Mormon (Sandstone) Fant (Andesite).	Sundance (Various strata). Twin Creek (Limestone).	Not named (Marine limestone resting upon Red Beds) Navajo (Pink sandstone). White Cliff
LOWER JURASSIC	Lias	Hardgrave (Sandstone) Modin (Trail?) (Various strata) (Missing)	Nuggett (Sandstone).	Todilto (Limestone and shale). Wingate (Red sandstone) Vermilion Cliff

Character of the Rocks. *Pacific Coast.* — The Jurassic strata of the Pacific Coast, from southern California to southwestern Alaska, are largely of marine origin. Various kinds of strata are represented, and these are usually moderately metamorphosed. Dark slates are perhaps the most common. The strata are nearly everywhere closely associated with igneous material, this being particularly true in British Columbia where the Jurassic system is unusually thick — 8000 to 18,000 feet — and volcanic rocks constitute about one-half of it.

One of the best Jurassic sections is in the Taylorsville region of northeastern California where about 6000 feet of non-metamorphosed marine strata and associated volcanic rocks have been subdivided into a number of formations as listed in the preceding table (Mariposa slate excepted).

In the Coast Range and Sierra Nevada Mountains of California the extensively developed Jurassic rocks are usually more or less metamorphosed and folded, being known as the Franciscan series in the Coast Range and the Mariposa slate in the Sierra Nevada.

Western Interior. — In the western interior of the continent, Triassic and Jurassic strata often have not been satisfactorily separated, but extensive Red Beds (with gypsum) of continental origin, like those of the Triassic system of the region, are doubtless of Jurassic age. A good idea of the character and order of these rocks may be gained from the formations listed under the Colorado Plateau in the preceding table. These formations reach a combined thickness of 2000 to 3000 feet. In the walls of Zion Canyon, Utah, a continental formation of nearly horizontal, massive sandstone over 2000 feet thick is wonderfully exposed. It is red in its lower portion, and white in its upper portion (Fig. 155). The lower part of this great formation may possibly belong to the Triassic.

Fig. 154

Structure section through a portion of the central Sierra Nevada Mountains, exhibiting the highly folded character of the Jurassic and late Paleozoic rocks *Ccg, Cch* = Mississippian or Pennsylvanian slate and some limestone; *Am, Db, Sp* = Jurassic (or early Cretaceous) amphibolite, diabase, and serpentine respectively; *Na* = Tertiary lava, *Ng* = Tertiary gold-bearing gravel Length of section about 11 miles (After Lindgren, U S Geological Survey, Folio 66)

The only known true, marine, Jurassic strata in the western interior are of Upper Jurassic age. These marine rocks, which comprise all types of ordinary sediments, especially limestones and shales, are usually highly folded or tilted in the Rocky Mountains, Wasatch Mountains, Black Hills, etc., and hence are there generally exposed only in narrow belts. The greatest thickness of these rocks in the western interior seems to be several thousand feet in southeastern Idaho and western Wyoming where they constitute the Twin Creek formation. Elsewhere the marine strata are seldom more than a few hundred feet thick. All of the Upper Jurassic marine strata of the western interior of the continent occur within the area represented as having been occupied by sea water on map Fig. 156. Overlying the marine Jurassic in the western Great Plains region there is a very late Jurassic formation (Morrison) of continental

origin and remarkable because so many remains of great Reptiles have been found in it.

Thickness of the Jurassic. — The thickness of the system in California is known to reach fully 6000 feet, while in western Nevada 5000 to 6000 feet of limestones and slates are reported. In Alaska a maximum thickness of 15,000 feet has been found, and in British Columbia, 18,000 feet. Throughout the western interior the thickness never appears to be great, usually not more than a few thousand feet.

Fig 155

Jurassic sandstone (red below and white above) over 2000 feet thick in the walls of Zion Canyon, Utah Bottom portion may be Triassic. (Photo by the author)

Igneous Rocks. — Tremendous bodies of granite have been intruded into rocks as young as the Late Jurassic (Mariposa) slates on the Pacific Coast, particularly in California. These intrusions occurred toward the close of the Jurassic period, as an accompaniment of the Sierra Nevada Revolution (see beyond). Granite of this age is wonderfully exposed in the walls of Yosemite Valley, California (Fig. 157).

Mention has already been made of the occurrence of vast amounts of volcanic rocks in the Jurassic system of the Pacific Coast.

Physical History

Pacific Coast. — The Pacific Coast region of North America seems to have been above sea level in earliest Jurassic time. Then the waters encroached upon the land, covering most of California,

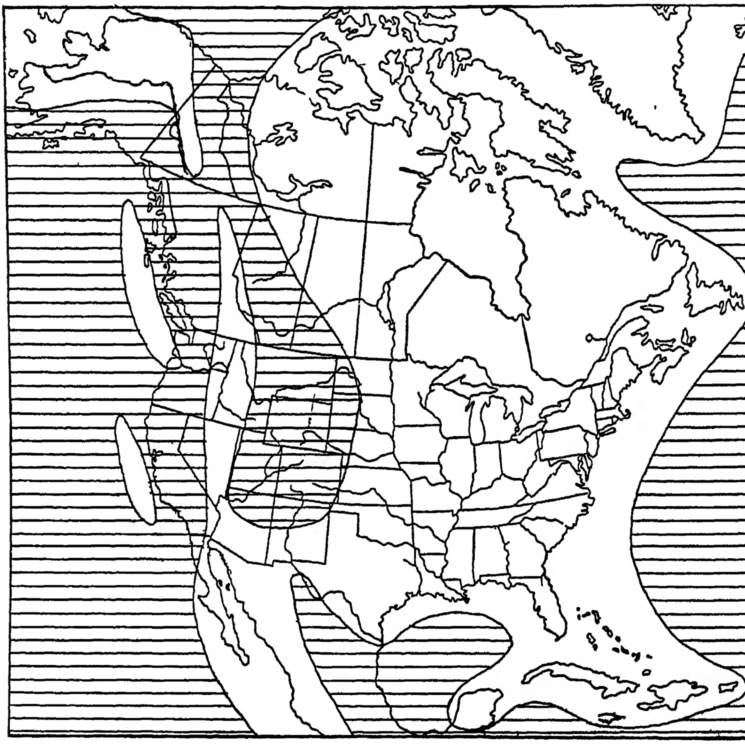


Fig 156

Paleogeographic map of North America during early Upper Jurassic time White areas, land, ruled areas, sea. (Principal data, modified by the author, from maps by B Willis and C Schuchert)

western Nevada, southern Oregon, western British Columbia, and the fringe of southern Alaska. Barring relatively minor changes, the marine waters became more extended until they reached the climax for the period. This was in Late Jurassic time when al-

most the entire Pacific Coast from southern California to southwestern Alaska was submerged, as shown on map Fig 156. At this same time eastern Mexico was also submerged. As in the Triassic, tremendous volcanic action, mostly of submarine character, took place, especially in the western British Columbia area. By the close of the period the sea withdrew from the whole Pacific Coast region.

Western Interior. — During Early and Middle Jurassic time there was deposition of more or less Red Beds material over the central portion of the western interior, especially in the states of Wyoming, Colorado, Utah, northern Arizona, and northern New Mexico. These rocks are excellently exposed in the Colorado Plateau where they are usually 2000 feet or more in thickness. Some of the principal formations are listed in the preceding table.

An important change occurred in the Late Jurassic, namely, the spreading of a shallow sea southward from the Arctic Ocean to the east of Alaska to central Arizona and New Mexico. This arm of the sea, or great mediterranean, was 600 miles wide in the western interior of the United States, and considerably narrower in Canada as shown on map Fig. 156. Some of the principal formations are the Sundance and Twin Creek of the Wyoming region, and the unnamed formation in the Colorado Plateau, all of which are rich in fossiliferous limestone.

Well before the close of the period, the interior sea vanished, and renewed Red Beds deposition occurred. Among these continental formations are the Morrison and McElmo, each several hundred feet thick.

Eastern North America in the Jurassic. — No Jurassic strata now occur in the eastern two-thirds of North America and we have no evidence that any ever were deposited there, hence that vast area was dry land undergoing erosion during the whole period. The period was ushered in by a considerable upwarping of the Atlantic border accompanied by some faulting and tilting, particularly of the Triassic (Newark) rocks, as shown in Fig. 140. That this uplift actually occurred, and that the Jurassic period in the eastern United States was a time of extensive erosion, is well established, because the whole Atlantic seaboard, including the tilted and faulted Triassic strata, was worn down toward the condition of a peneplain and the next sediments (Lower Cretaceous) were deposited upon the eastern portion of that worn-down surface. For instance, on Staten Island and in northern New Jersey, the Lower

Cretaceous beds may be seen resting directly upon the deeply eroded Triassic rocks, and hence the proof is conclusive that during much, if not all, of the Jurassic period active erosion was taking place, and this in turn implies that the Triassic beds were well elevated in the early Jurassic.

Close of the Jurassic (Sierra Nevada Revolution). — The close of the period witnessed profound geographic changes in the

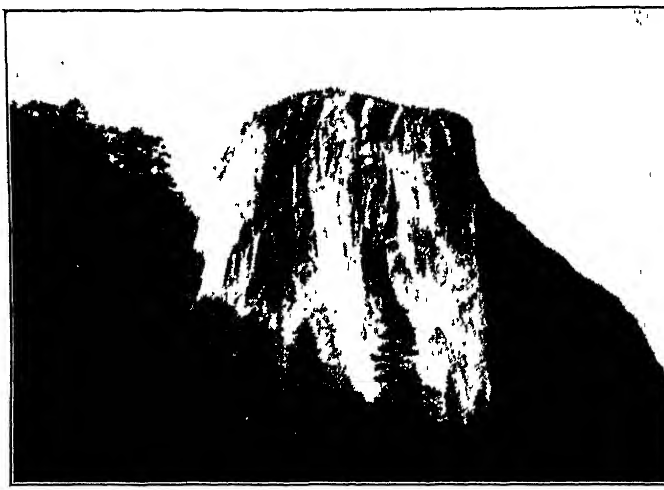


Fig 157

A great outcrop of Late Jurassic massive granite in El Capitan, Yosemite Valley, California (Photo by the author.)

western part of the continent. During both the Triassic and Jurassic periods, as well as throughout much of Paleozoic time, there had been more or less continuous deposition of sediments on the Pacific slope over the sites of the present Sierra, Cascade, and Coast Range Mountains. Toward the close of the Jurassic period these thick sediments, particularly in the Sierra region, were subjected to a tremendous force of lateral compression, the strata being upheaved, folded, and crumpled (Fig. 154). Thus the Sierra Nevada Mountains of California were borne out of the ocean and the Pacific shore line was transferred to the western base of the newly formed range. The Sierra Nevada Mountains, in this their

youth, were most likely a lofty range, but they were later much worn down by erosion, their present great altitude having been produced by later (Cenozoic) movements. Accompanying the orogenic movements, the deeply buried sediments were metamorphosed and the vast quantities of granite were probably intruded at the same time, this granite being now exposed to view only because of profound subsequent erosion. As a result of the metamorphism the

Fig 158

Late Jurassic (?) jointed granite weathering under desert conditions in the Pinto Mountains, Riverside County, California. (Photo by the author.)

thick Mesozoic shales were converted into the hard (Mariposa) slates.

The best evidence indicates that this orogenic disturbance also affected the strata of the Humboldt and other ranges of western Nevada; the mountains of southern California; the Klamath Mountains in northwestern California; and the Cascade Mountain region through Oregon and Washington, and, to some extent, even British Columbia. It is perhaps not too much to say that the whole Pacific Coast of the United States was more or less profoundly affected by the Sierra Nevada Revolution.

The strata then occupying the site of the present Coast Ranges were somewhat deformed, but probably only enough to form a chain of islands or a very low mountain range. This is proved by the fact that Lower Cretaceous strata are found resting unconformably upon the deformed Jurassic rocks. The orogenic movements which produced the Coast Range Mountains as we now see them came later.

The great arm of the sea or gulf which spread over the western interior region late in the Jurassic was drained as a result of these crustal disturbances. Hence we learn that all of North America was dry land at the close of the Jurassic period.

Foreign Jurassic

Europe. — The marine transgression which, in Late Triassic time, resulted in the submergence of the great salt lakes and other basins of central and western Europe, continued into the Jurassic. Even in the early (Lias) part of the period the sea covered considerable areas in western, central, and southern portions of the continent. The strata are mostly typical shallow sea sediments, though some coal-forming swamps existed around the sea borders in central Europe. These Early Jurassic strata are usually conformable upon and not sharply separated from the underlying Triassic

A progressive marine transgression continued through the middle of the period and well toward its close, extending farther and farther eastward, till much of the continent was submerged, as shown by Fig. 159. This was one of the greatest marine transgressions in the known geological history of Europe. As would be expected, the strata of later Jurassic age contain much more limestone than those of the earlier part of the period, because of the more widespread clear water areas. During all this time the great series of oolites were forming in England and the famous Solenhofen lithographic limestone was being deposited in southern Germany.

Just before the close of the period a considerable retrogression of the sea set in, draining certain areas and leaving lakes or estuaries in certain other places.

Other Continents. — Jurassic marine strata are known in many places in Arctic lands, thus showing extensive sea waters of that time there.

A great marine transgression also affected Asia, so that extensive areas of the continent became submerged, except mostly in the central portion. Widespread Jurassic deposits are known in Asia Minor, Siberia, India (especially the Himalayas), Persia, Turkestan, and Japan.

Jurassic rocks are also known in northern and eastern Africa, western South America, Australia, and New Zealand.

Fig. 159

Sketch map showing the relations of land and water in Europe during Late Jurassic time. White areas, land; ruled areas, sea. (Modified by the author after F. X Schaffer)

Climate

In general the evidence from the character and distribution of the organisms shows that the climate was comparatively mild Corals, for example, had a range several thousand miles farther northward than they do today. A careful study of the migrations

Fig. 160
A living Cycad, *Dioon edule*, of Mexico. (From a photograph by Prof. C. J. Chamberlain.)

of certain animals has, however, rather well established the fact that the Arctic Sea was notably colder than the Atlantic and Pacific, but it is perhaps too much to say that the northern sea was as cold as it is now. There was quite certainly some definition of climatic zones, especially in later Jurassic time.

Economic Products

The great gold-bearing veins or lodes of the famous "Mother Lode Belt" of the Sierra Nevada occur in Jurassic and older slates.

In California, also, important quicksilver deposits occur in metamorphosed Jurassic and later rocks.

Coal beds of some importance are found, mostly in the Lower Jurassic, in Hungary, various parts of Asia, and Australia.

As already mentioned, the famous Solenhofen lithographic stone of Bavaria is of Jurassic age.

Life of the Jurassic

In Europe, as would be expected because of the great sea transgression, the marine life was prolific, and a wonderfully rich record has been left and carefully studied by many paleontologists. Some idea of the profusion of marine organisms may be gained from the fact that more than 4000 species are known from the British Isles alone. The far less complete American marine record is in harmony with the adverse physical conditions.

Besides the marine fossils, the wonderful records of land animals, especially the remarkable and now extinct Mesozoic Reptiles, are worthy of particular mention.

Plants. — Viewed in a broad way, the plants of the Jurassic were much like those of the preceding period, though some progressive evolutionary changes took place. Certain characteristic Paleozoic plant-features, which were still found in the Triassic, finally disappeared in the Jurassic, and, as stated by Knowlton, "the Mesozoic life-forms were in full swing, expanding in the Middle and Upper parts of the period into an abundant and widespread flora." *Ferns*, *Equisetæ*, *Cycads* (Figs. 160, 161, 162), and *Conifers* continued to be the dominant forms, with the Cycads attaining their culmination in both number of individuals and species. The

Conifers took on a more modern aspect. The flora appears to have been remarkably uniform over wide portions of the world.

Protozoans. — *Foraminifers* and *Radiolarians* were both very abundant and highly diversified. Foraminifers are particularly numerous in certain Jurassic clays, while certain beds of chert or jasper are almost wholly made up of Radiolarian shells.

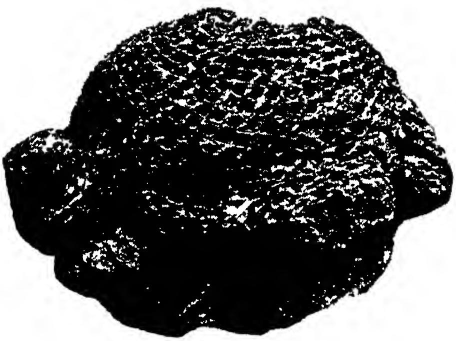


Fig 161

A fossil Cycad tree trunk, *Cycadeoidea pulcherrima* This is a Lower Cretaceous species (After Darton and W S Smith, U. S Geological Survey, Folio 108)

Porifers. — *Sponges* were very abundant and diversified. They are often beautifully preserved, even to the minutest details.

Cœlenterates. — *Anthozoans* (Corals) continued to be common, and all were of the modern *Hexacoralla* types.

Echinoderms.— After their culmination in the Mississippian, the *Crinoids* remained in a comparatively subordinate position during the Permian and Triassic periods. During the Jurassic they again became profuse. As regards both abundance and size they probably even surpassed those of the Mississippian, though not in diversity of species Their general structure was more like modern forms than like Paleozoic, and also there is good evidence that the shallow-water forms so common in the Paleozoic began to give way to deeper-water forms similar to those so prevalent today. Fig. 163 gives a good idea of one of the Jurassic Crinoids, the highly segmented and delicately branching arms being well exhibited. It scarcely seems credible that fully 600,000 segments have been counted in a single individual.

Asterozoans were moderately represented and they had already assumed a distinctly modern structure.

Echinoids. — These forms, which first attained much prominence in the Triassic, continued to increase in abundance and variety in the Jurassic. Early in the period regular forms only

existed, but later in the period the irregular forms made their first appearance. The regular forms were radially symmetrical, while the irregular ones were only bilaterally symmetrical (see Figs. 164, 165). Since the latter are distinctly more modern in structure, we

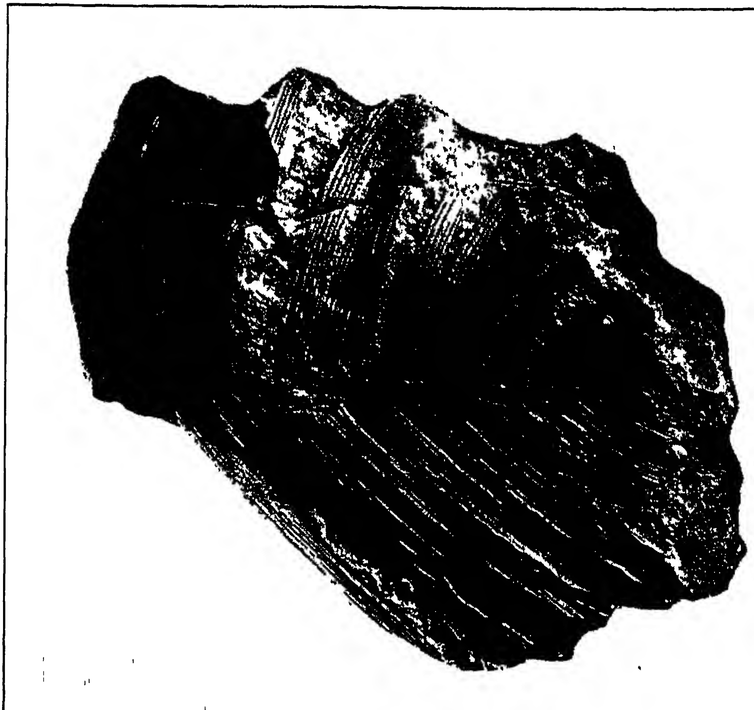


Fig. 162

Jurassic Cycad leaves (After Ward, U S Geological Survey, Monograph 48.)

have here another good illustration of progressive evolution toward modern forms.

Molluscoids. — *Bryozoans* were present, but apparently not very important.

Brachiopods were still fairly common, though the numbers of genera and species were reduced to only a few. Most of these genera have continued to the present day, so that in the succeed-

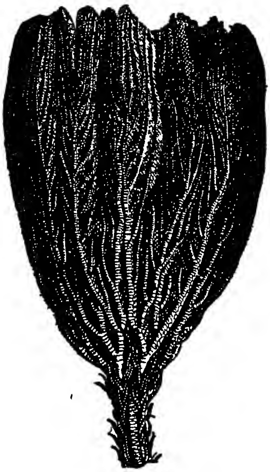


Fig. 163

A Jurassic Crinoid, *Pentacrinus fossilis* (After Goldfuss)

ing periods the evolution of these creatures, so very prominent in all of the earlier fossiliferous periods, has but little interest.

Mollusks. — *Pelecypods* were even more abundant than in any preceding period, their shells often largely constituting whole strata or thick beds. They were quite modern in appearance, many genera being those which still exist. The members of the *Oyster* family were most common, being represented by such genera as *Ostrea, Exogyra, Gryphea.*

Gastropods, including various existing genera, were usually common.

Among *Cephalopods* the ancient and important straight-shelled *Orthoceras* had disappeared with the preceding period, but coiled *Nautiloids* still were common. The *Ammonoids* reached the very height of their development in the Jurassic. Among these, the most characteristic and abundant were the *Ammonites,* in which the sutures or partition structures reached the highest degree of complexity (see Fig. 166). Many hundreds of species are known, and often Jurassic strata are chiefly composed of them. Of all coiled Cephalopods, the largest were of this age, some Ammonites having attained a diameter of several feet. In many cases "erratic and degenerate developments showed themselves by uncoiling and strange coiling, presaging a stage of 'sporting' and retrogression in the next period, followed by extinction" (Chamberlin and Salisbury). The reader is again referred to the table in Chapter VII which outlines the evolution of the chamber-shelled Cephalopods.

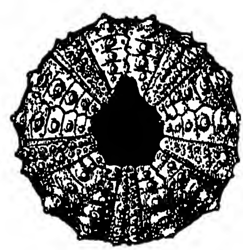


Fig 164

A regular or radially symmetrical Echinoid, *Pseudodiadema texanum,* of Lower Cretaceous age. (After Hill and Vaughan, U S. Geological Survey, Folio 76.)

We learned that the *Dibranch* Cephalopods made their first appearance in the Triassic period. In the Jurassic these forms were exceedingly abundant both in numbers of species and of individuals. Most characteristic of these were the *Belemnites*, so called because of the long, conical, or dart-shaped, internal shells which are generally the only portions preserved in the fossil state (see Fig. 168). They were similar in appearance to the modern Squids or Cuttlefishes. Some Jurassic forms reached a length of over two feet. A few specimens from the English Oölite show almost perfect preservation of the original creature (see Fig. 169). Ink-bags, like those found in modern Squids, are sometimes so well preserved that drawings of the fossils have actually been made with ink taken from their own ink-bags.

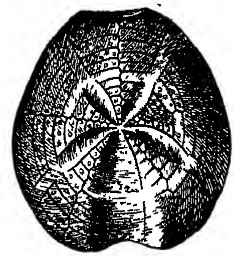


Fig 165

An irregular or bilaterally symmetrical Echinoid *Hemiaster texanus*, of Cretaceous age (After Hill and Vaughan, U S. Geological Survey, Folio 76.)

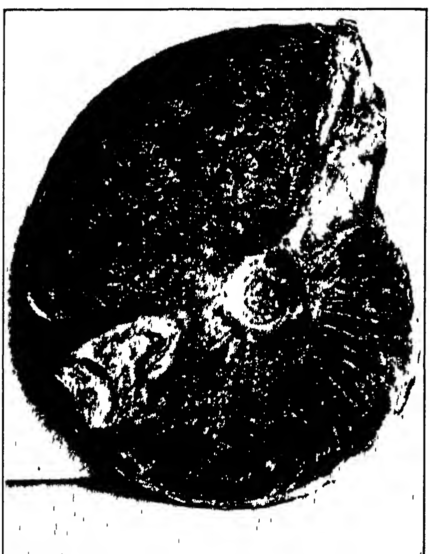


Fig. 166

A Jurassic Ammonite, *Ammonites guibalianus*, with part of the shell removed, showing the complicated suture or partition structure (Photo by the author.)

Arthropods. — Among the *Crustaceans* the familiar Paleozoic Trilobites and Eurypterids were, of course, gone, and forms much higher in structure had become abundant and of rather modern aspect. Thus, among Eucrustaceans, the long-tailed *Decapods* (*Macrurans*) or *Lobster* forms showed many genera and species (Fig. 170), while the short-tailed Decapods (Brachyura) or *Crab* forms made their first appearance,

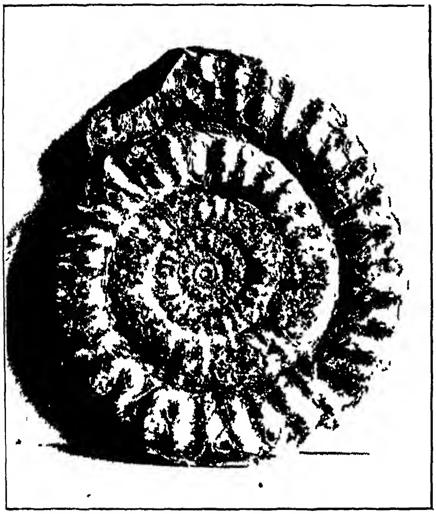


Fig. 167

A highly coiled Jurassic Ammonite, *Microderoceras birchi*. (Photo by the author.)

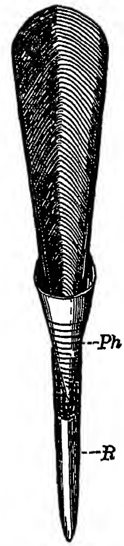


Fig. 168

Internal shell of a Belemnite, restored (From Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

though they were not numerous. Many types intermediate between the long-tailed and short-tailed Decapods were very common, these connecting forms being of special evolutionary interest because, in the embryonic development of the modern Crab, the long tail of the early stage gradually becomes shorter and practically absent in the adult stage. This is an excellent example of the so-called "Law of Recapitulation" (see Fig. 171).

Insects were numerous in certain localities at least, some hundreds of Jurassic species being known. There were many species of the simpler forms, including *Grasshoppers*. Among higher forms the *Beetles* became very abundant, while *Flies* and still higher Insects such as *Bees*, *Ants*, *Butterflies*, and *Wasps* made their first appearance in the Jurassic. The Insect life of the world was, therefore, remarkably modern in aspect thus far back in geological time.

Fishes. — *Selachians* continued to be common; *Dipnoans* were rare; and *Ganoids* were still the predominant Fishes. A very im-

portant change, showing progress among the Fishes, took place with the first appearance of the *Teleosts* or true bony Fishes, which types prevail today. The Jurassic forms were simple, not numerous, and they were frequently on the border between true Ganoids and true Teleosts (Fig. 172).

Fig. 169

A Jurassic Belemnite, *Belemnoteuthis antiqua*. (Modified after Mantell)

Amphibians. — Little or nothing is known concerning Jurassic Amphibians. This is in marked contrast with their prominent development in several immediately preceding periods. By the close of the Triassic they are known to have greatly diminished, never again to rise to prominence. Only a few small forms, such as Frogs, Newts, and Salamanders, represent this once great class at the present time.

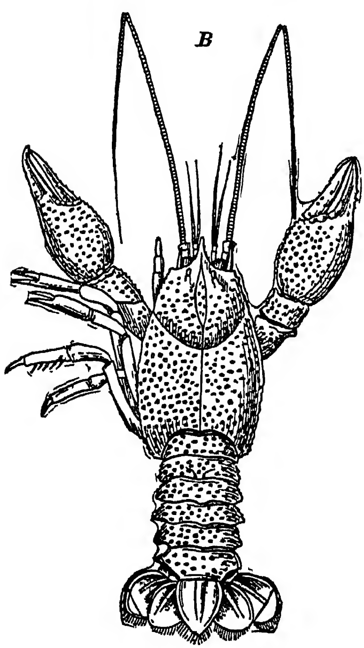


Fig 170

A Jurassic long-tailed Decapod (Macruran) (After Neumayr's "Erdgeschichte," from Schuchert's "Historical Geology," courtesy of John Wiley and Sons.)

Reptiles. — Viewed in the broadest way, the Reptiles of the Jurassic were much like those of the Triassic, except that they became more numerous and diversified. By some, this period is regarded as the culminating time of the Reptiles. As compared with the Triassic all the same principal groups were still represented, though with many genera and species changes. The more modern forms, such as *Turtles*, greatly increased, but *Lizards* were still very subordinate. *Crocodiles*

made their first appearance. As with all the Mesozoic periods, the principal interest surrounds the great groups of remarkable

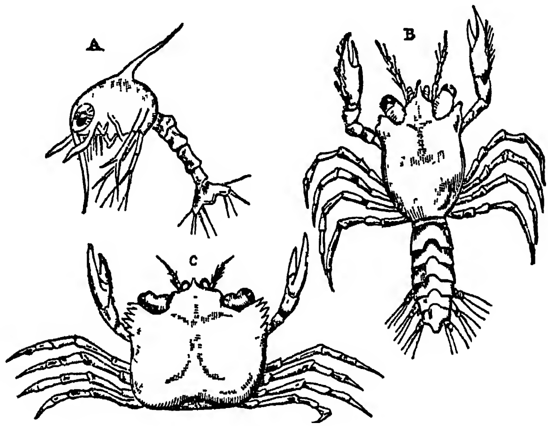


Fig 171

Three stages in the life history of a modern Crab The larval stage *B* is very similar to the adult Jurassic form shown in Fig 170 (After Couch, from Le Conte's "Geology," permission of D. Appleton and Company)

extinct Reptiles such as *Enaliosaurs*, *Dinosaurs,* and *Pterosaurs.* It will be more convenient, however, to describe Mesozoic Reptiles together toward the end of the next chapter.

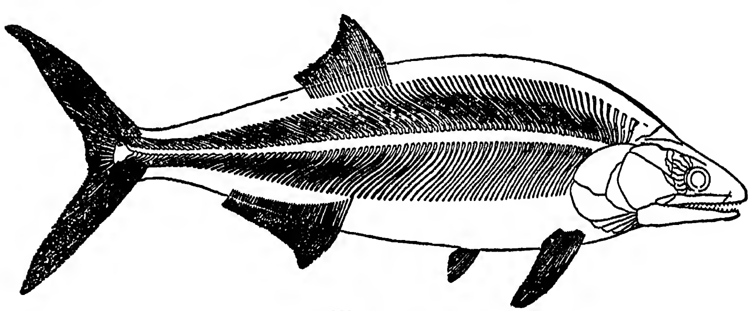


Fig 172

A primitive or ancestral Jurassic Teleost, *Hypsocormus insignis.* (From Scott's "Geology," courtesy of The Macmillan Company.)

Birds. — A very important feature from the standpoint of evolution was the introduction of the feathered creatures in the Jurassic. "The class of Birds is now so distinctly separated from all others and the connecting links obliterated, that the earliest Birds are of especial interest as throwing light on the evolution of this class. Until 1862 Birds had been found only in the Tertiary, and these were already distinctly differentiated as typical Birds. But in that year there was found in the Solenhofen (Bavaria) limestone, so celebrated for its marvelous preservations of organisms,

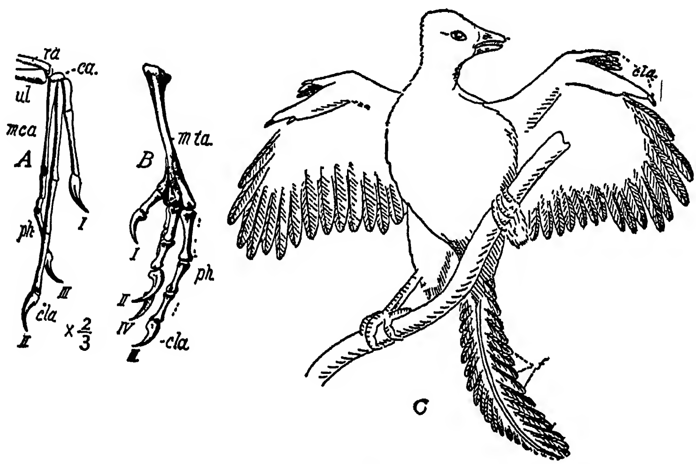


Fig 173

The earliest known Bird, *Archeopteryx macrura*, from the Jurassic. *A*, right hand; *B*, right foot; *C*, restoration modified after Pycraft. (From Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company.)

a flying feathered biped, and therefore presumably a Bird. But how different from our usual conceptions of this class! Along with its distinctive Bird-characters of feet, limb-bones, beak, and especially of feathered wings, it had the long tail and toothed jaws (see Fig. 173) of a Reptile. The structure of the tail is especially significant. In ordinary Birds the tail proper is shortened up to a rudiment and ends in a large bone, from which radiate the feathers of the tail-fan. In this earliest Bird, on the contrary, the tail proper is as long as all the rest of the vertebral column put together,

consisting, as seen in the figure, of twenty-one joints from which the fan feathers come off in pairs on each side. The tail-fan of this Bird differs from that of typical Birds precisely as the tail-fin of the earliest Fishes differs from that of typical Fishes. The tail-fan of this earliest Bird, like the tail-fin of the earliest Fishes, was vertebrated. This wonderful reptilian Bird was called Archeopteryx ('primordial winged creature'), and the species macrura ('long-tailed'). . . . So complete is the mixture of the two kinds of characters that some zoologists believe that the reptilian characters predominate, and that it should be called a Bird-like Reptile. Most agree, however, that it is a reptilian Bird."[1] Thus, while the evidence seems conclusive that Birds were evolved from Reptiles, there is no conclusive evidence that they were derived from the flying Reptiles (Pterosaurs). Rather there appears to have been a development of these two remarkable groups of flying creatures alongside each other.

Mammals. — This important class, first known from the Triassic, continued to be represented by only comparatively few small, very primitive forms in the Jurassic. The scant records show these creatures to have been no larger than Mice or Rats and low in organization (i.e *Monotremes* or *Marsupials*). As already stated, Mammals remained very subordinate throughout the Mesozoic era.

[1] J. Le Conte: *Elements of Geology*, 5th ed., pp 462–463.

CHAPTER XVI

THE CRETACEOUS PERIOD

ORIGIN OF NAME, SUBDIVISIONS, ETC.

THE term *Cretaceous*, from the Latin "Creta" for chalk, was given to the period because of the prominence of chalk beds in the rocks of this age, especially in England and France. In fact, one of the most striking features of the landscape in southern England and northern France consists in the frequent exposures of beds of white or very light colored chalk. Perhaps the most famous are the Dover Cliffs of England. In many parts of the world, however, the Cretaceous system is not rich in chalk deposits. In the United States, chalk is extensively developed in the Cretaceous of Alabama and Texas. The system was first carefully studied in England, but the names of the French subdivisions are now more widely employed.

For a long time the Cretaceous system has been known to be divisible into two portions — a Lower and an Upper — often separable by unconformity, and, during the past ten or twelve years, some authors have regarded the Lower Cretaceous as a separate system called "Comanchean" from a locality in Texas.

Following are the principal subdivisions of the Cretaceous as now recognized in Europe and North America, though exact correlations are not implied (see next page).

DISTRIBUTION AND CHARACTER OF THE ROCKS

General Distribution. — *Lower Cretaceous.* The surface distribution of rocks of known Lower Cretaceous age is shown on the accompanying map (Fig. 174). With the exception of part of Virginia,[1] these rocks are seen to form a narrow outcropping belt at the western margin of the Atlantic Coastal Plain from New Jersey to Alabama. Passing eastward from the exposed belt, well

[1] In this part of Virginia the Lower Cretaceous strata are completely concealed under Tertiary strata.

	European	North Atlantic Coastal Plain	Alabama	Texas	Great Plains	California
Upper	Thanetian	Shark River			Fort Union	
	Danian	Manasquan Rancocas	(Absent)	Navarro	Lance Laramie	
	Senonian	Monmouth Matawan	Selma-Ripley	Taylor	Montana	Chico
	Turonian	Magothy	Eutaw Tuscaloosa	Austin Eagle Ford Woodbine	Colorado Dakota	
	Cenomanian	Raritan.				
		(*unconformity*)	(*unconformity*)	(*unconformity*)		(*unconformity*)
Lower	Albian	Potomac: Patapsco	(Absent)	Washita		Horsetown
	Aptian	Potomac: Arundel		Fredericks-burg		
	Barremian		Lower Cretaceous		Lakota	Knoxville.
	Neocomian	Potomac: Patuxent		Trinity	Kootenai	

borings show that a large part of the whole Coastal Plain is underlain with Lower Cretaceous rocks. "The sediments (of the Coastal Plain) in general form a series of thin sheets which are inclined seaward (Fig. 181), so that successively later formations are encountered in a journey from the inland border of the region toward the Coast" (W. B. Clark).

As the map shows, the most extensive surface distribution of Lower Cretaceous rocks is in Mexico and Texas. Here, too, in passing toward the (Gulf) Coast these strata are known to be extensively developed under cover of later formations. In general, therefore, the actual extent of Lower Cretaceous strata in the Atlantic and Gulf Coastal Plain is much greater than the surface exposures.

Several small areas are known in the western United States in the Rocky Mountains and in the Coast Range of northern California. Large surface areas occur in British Columbia and Alaska. In many of these western regions the Lower Cretaceous strata are notably folded or tilted, so that their full extent is not shown by the outcrops.

Upper Cretaceous. As seen on map Fig. 175, the rocks of Upper Cretaceous age are widely exposed at the surface — much more so than those of Lower Cretaceous age. In the eastern and southern United States, Upper Cretaceous strata outcrop as comparatively long, narrow belts at or near the western and northern

margin of the Atlantic and Gulf Coastal Plain. The northernmost exposures are on Martha's Vineyard. The occasional gaps shown

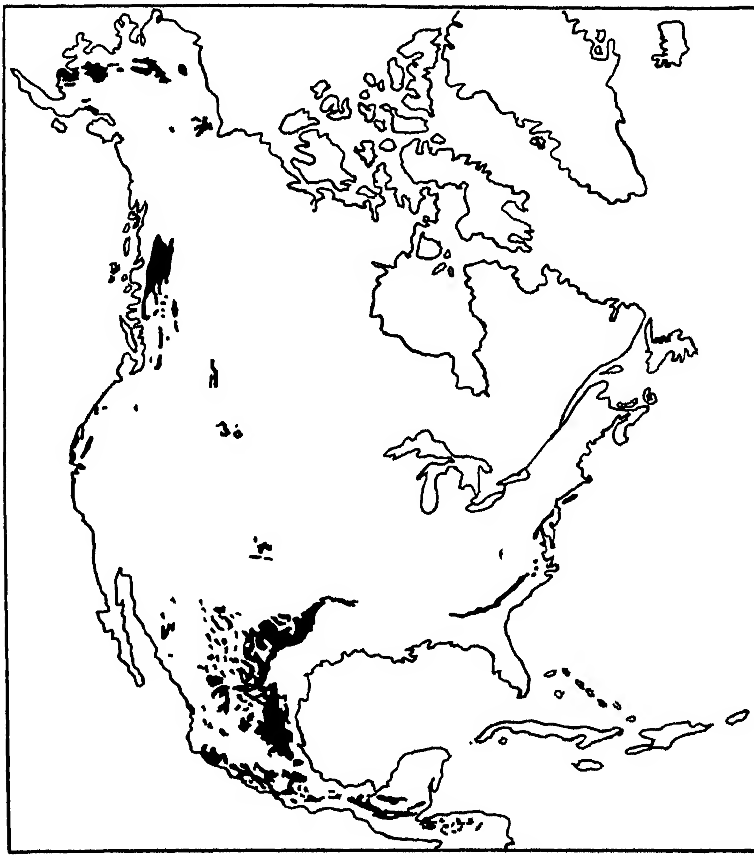


Fig. 174

Map showing the surface distribution (areas of outcrops) of Lower Cretaceous strata in North America. (Modified by W. J. M. after Willis, U. S. Geological Survey.)

on the map are due to the fact that the Upper Cretaceous beds are there concealed under later deposits. From the outcropping belts oceanward or gulfward, the Cretaceous strata dip gently under the

later (Cenozoic) deposits and they there underlie much, if not all, of the Coastal Plain (Fig. 181).

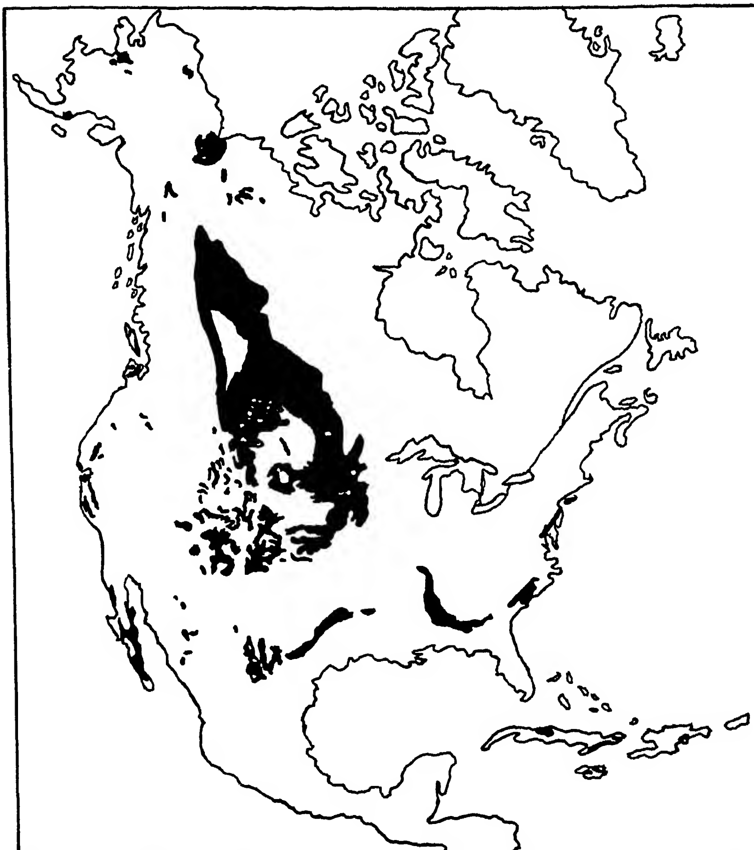


Fig 175

Map showing the surface distribution (areas of outcrops) of Upper Cretaceous strata in North America (Modified by W J M. after Willis, U S. Geological Survey)

A large part of the western interior shows Upper Cretaceous rocks at the surface. Because of the usual only slightly deformed character of the strata just west of the main axis of the Rocky

Mountains, there is a large practically solid outcropping area, while within the Rockies, where much deformation has affected the rocks, the outcrops are much more patchy in distribution. Large areas of Upper Cretaceous strata are also concealed under later rocks in this western interior region (Fig. 175).

On the Pacific Coast and in Alaska only small areas of Upper Cretaceous strata show at the surface, but since the rocks there are usually in a highly deformed condition, they are really considerably more extensive than the surface exposures seem to indicate.

Character of the Rocks. — *Atlantic Coastal Plain.* Three well-known Lower Cretaceous formations (Patuxent, Arundel, and Patapsco) of the Atlantic Coast have long been called the *Potomac series.* They are all of continental origin. They consist mainly of sands and clays with a total thickness of about 725 feet. The sands are often cross-bedded, and some of the clays are highly colored. Fossil plants are common, and in some places there are beds of lignite. Several small unconformities occur within the Potomac series.

The Upper Cretaceous deposits rest unconformably upon the Lower Cretaceous. According to Clark the Upper Cretaceous formations of New Jersey are typical of the North Atlantic Coastal Plain. They consist mainly of clays, sands, gravels, and greensand (glauconitic) marls with a total thickness of about 1000 feet. There are some lignitic and limy beds. These Upper Cretaceous deposits have been subdivided into a number of formations separated by minor unconformities. Some of the best known of these formations are listed in the preceding table.

Alabama. Lower Cretaceous strata of Alabama, according to Stephenson, consist of "irregular bedded, coarse, arkosic, more or less micaceous sand, with subordinate lenses of usually massive clay of greater or lesser purity. The terrane rests upon a basement of crystalline rocks and is separated from the overlying Eutaw and other Upper Cretaceous and Tertiary formations by an unconformity." [1]

According to Stephenson the Upper Cretaceous formations consist mainly of variously bedded sands, greensands, clays, gravels, impure limestones, and chalk. Their total thickness is fully 2600 feet. The *Selma* chalk, very rich in Foraminiferal shells,

[1] L. W. Stephenson: U. S. G. S., *Professional Paper 81*, p. 20.

is a striking, white formation, reaching a thickness of nearly 1000 feet.

From the above descriptions, the Atlantic and eastern Gulf Coastal Plain Cretaceous deposits are seen to be largely unconsolidated. They are only slightly tilted sediments. The Lower Cretaceous strata are largely non-marine, while the Upper Cretaceous are largely marine.

Texas. In the Texas region the *Trinity* formation consists mostly of light colored sands, with some alternating marls, clays, and limestones. Its lower portion is of continental origin, while its upper portion is marine. The whole formation attains a maximum thickness of about 2000 feet. The *Fredericksburg* formation is typically almost entirely chalky limestone of marine origin from 1000 to 5000 feet thick. It covers wide areas in Mexico and Texas. The *Washita* formation comprises chiefly alternations of light and dark colored marly clays, limestones, and sandy limestones whose thickness is from 200 to 400 feet. This formation extends across much of Mexico, Texas, and northward into Oklahoma, southeastern Kansas, eastern Colorado, and possibly into Wyoming.

The *Woodbine* formation, according to Hill,[1] is made up of ferruginous sands and clays (600± feet thick), the *Eagle Ford* formation is essentially bituminous clay with some limestone (600± feet thick); the *Austin* formation is largely impure chalk with some softer beds of marl (600± feet thick), the *Taylor* formation is calcareous clay marl (several hundred feet thick); and the *Navarro* formation is mostly made up of sands, chalks, and clays with some glauconite (thickness?).

Great Plains. In the Great Plains region, mostly just east of the main axis of the Rocky Mountains from Colorado northward, there occur certain formations — *Lakota, Kootenai,* etc. — which consist mostly of shales, sandstones, and much coal. They are Lower Cretaceous deposits of continental origin.

The *Dakota* formation is chiefly sandstone, mostly of marine origin, usually several hundred feet thick. The *Colorado* formation is very largely of marine origin and comprises mostly clastic sediments but with considerable chalk. The *Montana* formation comprises mostly clastic sediments of marine origin, though with some continental deposits, as, for example, local coal beds. It shows a remarkable variation in thickness of from 8700 feet in

[1] U. S G. S., *Professional Paper 71*, pp. 20–21.

Colorado to only 200 feet in the Black Hills of South Dakota. The *Laramie* formation is quite certainly mostly of non-marine origin, with fresh-water and land deposits (including much coal) common. The formation shows a variable thickness possibly up to several thousand feet. The *Lance* formation, in part marine and in part continental in origin, attains a thickness of 700 feet in North Dakota. The *Fort Union* sands and clays of both fresh-water and subaërial origin reach a thickness of 2000 feet in North Dakota, Montana, and the Great Plains of southern Canada.

Pacific Coast. — On the Pacific Coast, the Lower Cretaceous is remarkably developed, where it shows a maximum thickness. In California the older or *Knoxville* series, comprising nearly 20,000 feet of shales with some interbedded sandstones and limestones, is overlain conformably by the *Horsetown* series of sandstones and shales about 6000 feet thick. This enormous thickness of sediments is clearly of shallow-water origin, the rocks now nearly always being distinctly folded or tilted. Lower Cretaceous strata, usually folded and sometimes metamorphosed, also are widely developed in British Columbia and Alaska with some coal in both regions and some volcanic rock in the former.

The Upper Cretaceous on the Pacific Coast is represented by the single great *Chico* formation, but both the oldest and the youngest portions of the series are often not represented at all. The Chico is a marine deposit from a few hundred to more than 5000 feet thick. It is prominently developed in the Coast Range Mountains from Lower California to British Columbia. It consists mostly of sandstones, shales, and conglomerates, and is, in some places, conformable, and in others unconformable, to the Lower Cretaceous.

Thickness of the Cretaceous. — The system shows a maximum thickness of fully 1700 feet on the north Atlantic Coast; 3000 + feet in the eastern Gulf region; 3500 to 7500 feet in the western Gulf region; 10,000 to 20,000 feet in the western interior region, though usually much less in any one locality; and 25,000 to 30,000 feet in California.

Igneous Rocks. — Volcanic rocks are associated with the Lower Cretaceous in British Columbia. Igneous rocks (chiefly lavas) of Late Cretaceous and Tertiary ages occur in vast quantities over great areas in central western North America. The igneous activity represented by these rocks is more fully described in succeeding pages.

Physical History

Atlantic and Eastern Gulf Coasts. — The Cretaceous period opened with the coast line of the eastern United States somewhat farther out than it now is, but, early in the period, there was enough subsidence, or possibly warping, of the coastal lands to allow deposition of sediments over much of what is now known as the Atlantic and eastern Gulf Coastal Plain. That but little downwarping of the surface was necessary in order to produce proper conditions for this sedimentation is evident, because the coastal lands just prior to the Cretaceous were already low-lying as a result of the long Jurassic erosion interval. There was just enough warping of the low coastal lands to produce wide flats, flood-plains, shallow lakes, and marshes back from the real coast line. Over such areas were deposited the sediments derived from the Piedmont Plateau and Appalachian areas. The very irregular arrangement of the deposits (Potomac) and their rich content of fossil land plants afford conclusive evidence that the sediments were accumulated under continental conditions.

The rather widespread unconformity between the Lower and Upper Cretaceous in these regions proves that, about the close of the Lower Cretaceous, there must have been enough emergence of the lands to convert the basins of deposition into areas of erosion. Early in the Upper Cretaceous, however, a submergence of the coastal lands took place, inaugurating the deposition of the Upper Cretaceous strata. The general character, mostly marine [1] origin, and present extent of these deposits prove that the submergence allowed a shallow sea to spread over much of what is now called the Atlantic and eastern Gulf Coastal Plain.[2] In this connection it is very important to note that *Appalachia*, the great land-mass which had persisted through the many millions of years of the Paleozoic era as well as most of the Mesozoic era, largely disappeared under the Cretaceous sea not again to appear in anything like its former magnitude.

Texas. — During most of Lower Cretaceous time a clear and unusually deep epicontinental sea occupied much of Mexico and Texas and immediately adjoining regions. Great chalk deposits

[1] Some beds of continental origin occur in the Upper Cretaceous of Maryland and New Jersey.

[2] Certain minor oscillations of level are here disregarded.

were formed in this clear sea. Perhaps the maximum northward extension of the Lower Cretaceous sea took place during late Lower Cretaceous (Washita) time, when marine waters probably reached as far northward as Colorado.

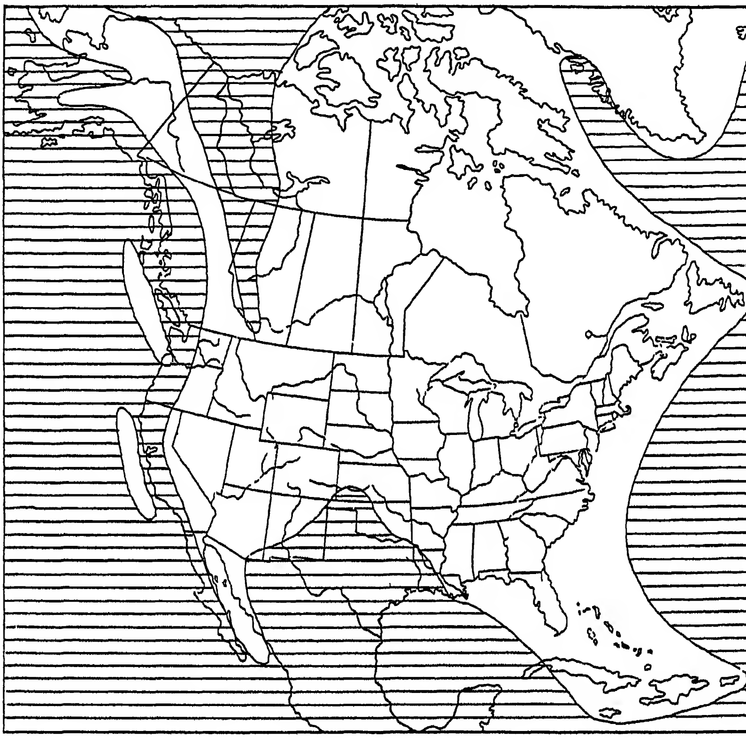


Fig. 176

Paleogeographic map of North America during middle Lower Cretaceous time White areas, land; ruled areas, sea. (Principal data, modified by the author, from maps by B. Willis and C. Schuchert)

Throughout Upper Cretaceous time marine waters appear to have persisted over the Texas area, having been particularly clear during the deposition of the Austin chalk. The eastern one-half of Mexico was also submerged.

Western Interior-Great Plains Region. — The physical history of this area during Lower Cretaceous time is still somewhat problematical, but the best evidence seems to show that, just east of the site of the Rockies, deposits of continental origin (Lakota and

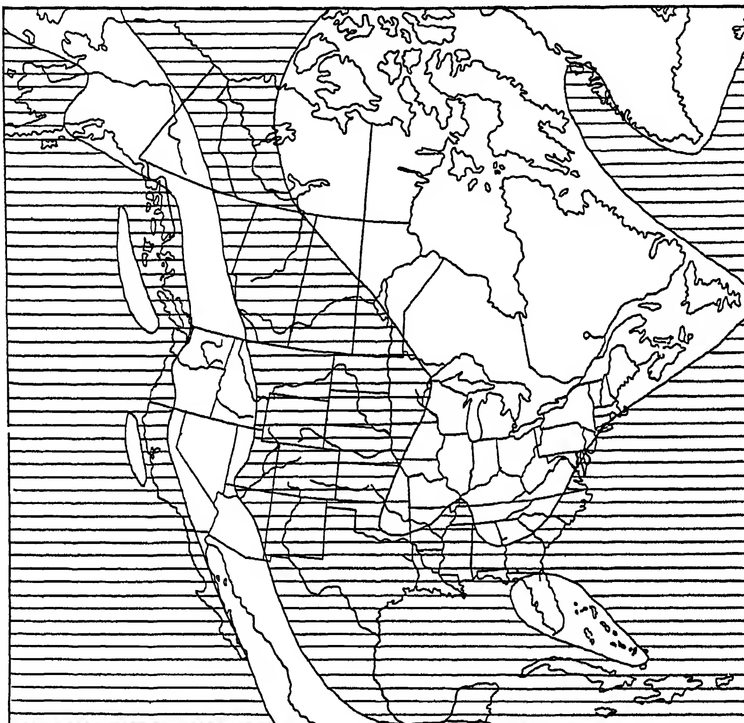


Fig 177

Paleogeographic map of North America during early and middle Upper Cretaceous time White areas, land; ruled areas, sea. (Principal data, modified by the author, from maps by B. Willis and C Schuchert.)

Kootenai) were forming very much like those of the Potomac on the Atlantic Coast.

Rather early in the Upper Cretaceous, the western interior-Great Plains region witnessed a very extensive marine transgression

beginning during Dakota time and probably reaching a maximum during Colorado time. In the comparatively clear waters of this sea there were laid down the chalk and other marine deposits. This great marine invasion must take rank as one of the most extensive in the history of the continent, the sea waters having spread from the Gulf of Mexico northward over the Rocky Mountain-Great Plains region to the Arctic Ocean by way of what is now the

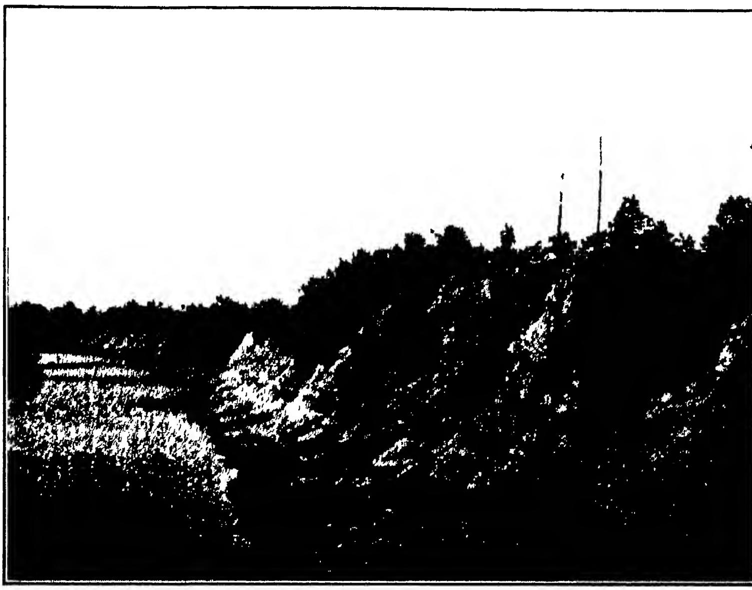


Fig. 178

Typical exposure of Upper Cretaceous (Selma) chalk in Alabama. (After L. W. Stephenson, U. S Geological Survey, Prof. Paper 81.)

Mackenzie River Valley (see map Fig. 177). There is no good evidence that this vast western interior sea had direct connection with the Pacific Ocean. In the latter portion of the period (Laramie) marine waters prevailed only over part of the Great Plains area of the United States. Sufficient emergence "formed a coastal plain, extensive marshes prevailed, and the marsh deposits became coal beds. Sea, marshes, and river plains alternated in sequence till near the close of the Cretaceous period" (Bailey Willis).

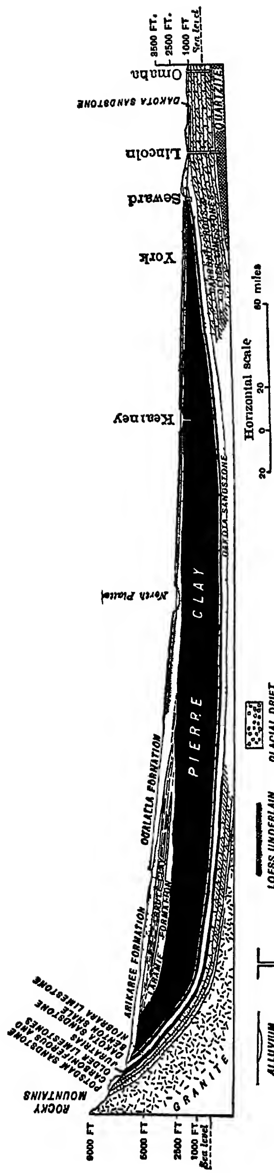


Fig. 179

Structure section across Nebraska from the Rocky Mountains to Omaha The Dakota, Benton, Niobrara and Pierre formations are Cretaceous. (After Darton, U S Geological Survey, Prof. Paper 17)

Pacific Coast. — Rather remarkable physical conditions must have obtained in California, especially in the north, to give rise to such a phenomenal thickness of sediments during this one period. Apparently the explanation is not far to seek, because the newly upraised Sierra Nevada must have undergone vigorous erosion with rapid accumulation of materials in the marine waters which then occupied the sites of the present Great Valley and Coast Range of California. An unconformity, indicating considerable uplift and deformation, usually separates the Lower and Upper Cretaceous in California.

In British Columbia and Alaska the presence of marine strata proves the existence of sea water over the areas indicated on the accompanying maps, though the coal beds show that great swamps or lagoons must have existed locally.

Close of the Period in the West (Rocky Mountain Revolution). — The close of the Cretaceous period, or, what is the same thing, the close of the Mesozoic era, was marked by one of the most profound and widespread physical disturbances in the history of North America since pre-Cambrian

time. Over the Rocky Mountain district there had been more or less deposition of sediments (both marine and continental) during Proterozoic, Paleozoic, and Mesozoic times. Toward the close of the Cretaceous, there was vigorous deformation, including both folding and dislocations of the strata, not only throughout the Rocky Mountain district in North America from the Arctic Ocean to Central America, but also even along the line of the Andes Mountains to Cape Horn — altogether more than one-fourth of the way around the earth. This great crustal disturbance has been called the "Rocky Mountain Revolution." While the folding was usually not nearly as intense as at the time of the "Appa-

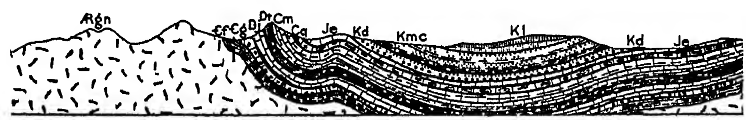


Fig 180

Structure section in the Rocky Mountains of western Montana showing moderate folding of Cretaceous and older rocks *Argn*, Archean, *Cg*, *Cf*, Cambrian; *Dt*, *Dj*, Devonian, *Cq*, *Cn*, Carboniferous; *Kl*, *Kmc*, *Kd*, Cretaceous. (After Peale, U. S. Geological Survey, Folio 24)

lachian Revolution," nevertheless there were very considerable uplifts accompanied by moderate folding of the strata in many parts of the district (Fig. 180).

The portion of the Rocky Mountains situated in the northern United States and southern Canada suffered the severest deformation, where strata 50,000 to 75,000 feet thick were folded and faulted into a mountain range probably no less than 20,000 feet high. Referring to this region Schuchert says that "there had been no orogeny from early Proterozoic time until the close of the Cretaceous. During this vast time there was laid down in this area about 20,000 feet of Mesozoic strata resting upon 26,000 feet of Paleozoic formations, and these in turn lie (almost) conformably upon about 30,000 feet of but little metamorphosed Proterozoic rocks. It is the longest accessible geological section known anywhere and attests to the striking fact that the earth's crust may subside at least 14 miles before it becomes folded into mountains."[1]

[1] C. Schuchert: *Geol. Soc. Amer. Bul.*, Vol. 34, 1923, p. 191.

The Rocky Mountains may be truly said to have had their beginning at the close of the Cretaceous, although their existing altitude and relief features are largely due to later movements and erosion. Instead of folds, great thrust faults were sometimes developed, a fine example being in Glacier National Park where Proterozoic rocks were pushed at least 12 miles over Cretaceous rocks.[1]

Another very important physical disturbance accompanying the "Rocky Mountain Revolution" in the western United States, Mexico, and southern British Columbia, was the inauguration of vast igneous (chiefly volcanic) activity, which continued almost unabated into the early part of the immediately succeeding Tertiary period.

Close of the Period in the East. The Cretaceous Peneplain and Its Uplift. — Turning our attention to the eastern part of the continent, we find that significant changes took place there also. In fact the area of the eastern United States was subjected to the greatest crustal disturbance since the "Appalachian Revolution" toward the close of the Paleozoic.

During all of the Mesozoic era most of the eastern portion of the United States, except the Coastal Plains during part of the time, was above sea water and undergoing erosion, so that, as a result of this very long time of wear, the region was reduced to the condition of a more or less perfect peneplain. It is known as the "Cretaceous Peneplain," because of its best development during the Cretaceous period (Fig. 181). This vast plain extended over the areas of the Appalachian Mountains, Piedmont Plateau, all of New York state, the Berkshire Hills, and the Green and White Mountains. Its most perfect development was in the northern Appalachians as, for example, from east-central Pennsylvania to Virginia, where hard and soft rocks alike had been so thoroughly cut down that no masses projected notably above the level of the low-lying plain.

Farther northward, however, over New York and western New England, and also farther southward as in North Carolina, its development was less perfect, so that certain masses of harder rock stood out more or less prominently above the general level of the plain.

[1] It is possible that this fault was developed a little later, that is in early or middle Tertiary time.

As Berkey says. "The continent stood much lower than now. Portions that are now mountain tops and the crests of ridges were then constituent parts of the rock floor of the peneplain not much above sea level. . . . The ridges and valleys, the hills, mountains, and gorges of the present were not in existence, except potentially in the hidden differences of hardness or rock structure. Such conditions prevailed over a very large region — certainly all of the eastern portion of the United States."[1]

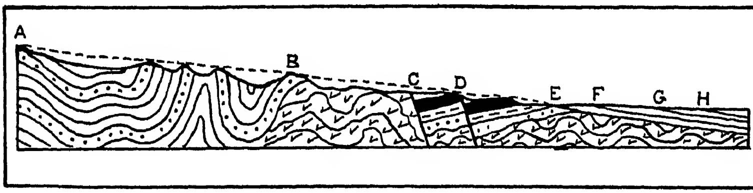


Fig 181

Diagrammatic section through the Atlantic slope at about the latitude of northern New Jersey, showing the structures and relations of the various physiographic provinces as they now exist

A to *B*, folded Paleozoic strata of the Appalachian Mountains, with hard strata standing out to form the ridges, *B* to *C*, Piedmont Plateau, consisting of highly folded and metamorphosed rocks of pre-Cambrian and early Paleozoic ages; *C* to *E*, Triassic strata, showing tilting and faulting of the beds and mode of occurrence of a sheet of igneous rock (*D*) which outcrops to form low ridges, *E* to *H*, Coastal Plain, consisting of comparatively thin sheets of unconsolidated sediments; *E* to *F*, Cretaceous beds; *F* to *G*, Tertiary beds; *G* to *H*, Quaternary beds; *H*, present coast line

The dotted line represents the peneplain character of the surface, except for the tilting, toward the close of the Mesozoic era (After W J Miller, *N Y. State Mus. Bul. 168.*)

The Cretaceous period was closed in eastern North America by a disturbance which produced an upwarp of this vast Cretaceous peneplain with maximum uplift of from 2000 to 3000 feet, following the general trend of the Appalachians and thence through northern New York and western New England. This upward movement was unaccompanied by any renewed intense folding of the strata, the effect having been to produce a broad dome sloping eastward and westward, and northward to the Gulf of St. Lawrence and southward to the Gulf of Mexico. The upward movement

[1] C. P. Berkey: *N. Y. State Mus. Bul. 146*, p. 67.

was, however, accompanied by the retreat of the sea from the Coastal Plain area, which thus accounts for the widespread unconformity there between the Cretaceous and the overlying Tertiary strata.

Another prominent effect of this great uplift was to revive the activity of the streams so that they once more became active agents of erosion, and the present major topographic features of the eastern United States have been largely produced by the erosion and dissection of this upraised Cretaceous peneplain. Where the peneplain was best developed, the typical Appalachian ridges and valleys, running parallel to the trend of the mountain range, are now beautifully shown. These valleys are the trenches of the upraised peneplain, while the ridges have developed along the belts of hard rock, their summits actually representing portions of the old peneplain surface (Fig. 181). These ridges all rise to the same general level for miles around, and as viewed from the summit of any one of them, the concordant altitudes give rise to what is called the "even sky-line," which is a most striking feature of the landscape (Fig. 212). In New York state and western New England remnants of the upraised peneplain surface are also distinctly shown.

Foreign Cretaceous

Europe. — Toward the close of the Jurassic and about the beginning of the Cretaceous, continental deposits were forming in parts of central and western Europe. Often these deposits grade from the Jurassic into the earliest Cretaceous. The Alpine region continued to be submerged under sea water. Soon after the beginning of the Cretaceous, a more or less interrupted marine transgression caused considerable areas of western and central Europe to become submerged, the deposits including both marine and non-marine beds. At the same time marine waters were more extended over the southern part of the continent. In western and central Europe all types of common sedimentary rocks were formed, as well as some beds of coal in Germany. As would be expected, because of the more prevalent marine conditions in southern Europe, limestone was more commonly formed there. The conditions just described continued essentially till the close of the Lower Cretaceous, when only comparatively slight sea retrogressions took place, as proved by the fact that

the Upper Cretaceous rocks usually rest conformably upon the Lower Cretaceous. Thus in Europe there is not such a sharp break between the Lower and Upper Cretaceous as in North America.

As in North America, so in Europe, Upper Cretaceous time

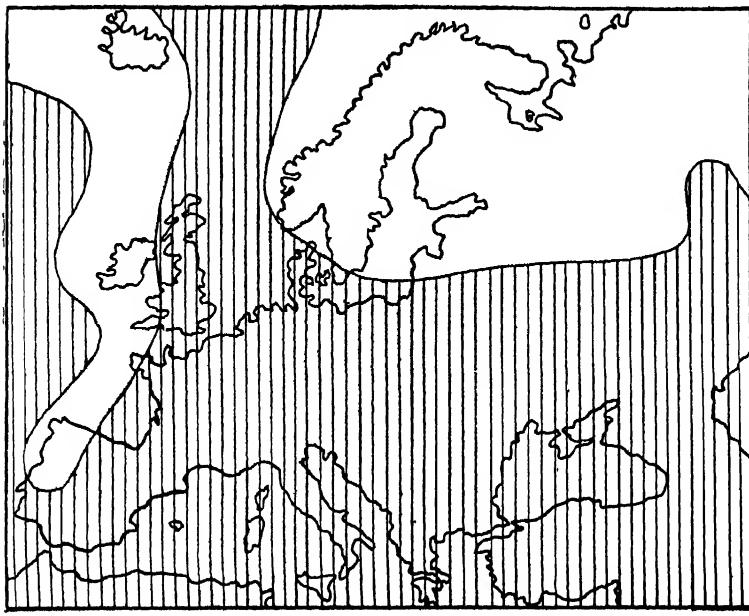


Fig. 182

Sketch map showing the relations of land and water in Europe during Upper Cretaceous time. White areas, land; ruled areas, sea (Modified by the author after F. X. Schaffer.)

was marked by a great transgression of the sea. This marine invasion, which started in the Lower Cretaceous, continued with only slight interruptions well into the Upper Cretaceous, when much of Europe, except Scandinavia and northern Russia, was submerged, as shown by map Fig. 182. As in the Lower Cretaceous, the most common rock to form in southern Europe was limestone. In central-western Europe all types of ordinary sediments

are represented, but, as already stated, in northern France and southern England, the Cretaceous contains much chalk (e.g. Dover Cliffs) which is made up of Foraminiferal shells and which implies clear, if not fairly deep, sea water for its accumulation. Considerable greensand also occurs in the European Upper Cretaceous.

Toward the close of the period (Danian time) there were upward movements sufficient to increase the land areas and establish basins of non-marine sedimentation from Spain to and across the Alpine region as shown by the Cretaceous fresh-water deposits there.

Other Continents. — Rather extensive areas of Cretaceous occur in New Zealand and Australia, where the rocks are frequently coal bearing and an unconformity often separates the Lower and Upper portions of the system.

Southwestern Asia, India (in the Himalayas), China, Japan, and Siberia all show more or less extensive development of Cretaceous strata. Over northern Africa extensive areas of marine Cretaceous rocks show much of that region to have been submerged during the period. In South Africa Cretaceous rocks (especially the Lower) are considerably developed. A feature of special importance in India was the inauguration, late in the period, of one of the greatest times of vulcanism since the pre-Cambrian and quite comparable to that of western North America already referred to. This is known as the Deccan lava region where some 200,000 square miles are covered by lava flows whose aggregate thickness reaches several thousand feet.

In South America Cretaceous rocks are widely distributed, especially in Brazil, where a notable marine invasion occurred in the Upper Cretaceous, though in places only continental deposits were formed. East of the Andes the Lower Cretaceous rocks are mostly non-marine. High in the eastern Andes and in southern Patagonia marine Upper Cretaceous strata are known. Toward the close of the period came the great orogenic disturbance, accompanied by much volcanic activity, in the Andes Mountains district.

Climate

As would be expected because of the unusually extensive epicontinental seas, the climate of the period seems to have been mild to warm and rather uniform but with some distinction of

climatic zones. The fossil evidence (e.g. plants in the Cretaceous of Greenland) indicates mildness of climate even within the Arctic circle.

Economic Products

Coal beds of moderate extent and value are known in the Lower Cretaceous rocks of Alaska, British Columbia, Australia, and Germany.

Coal is extensively developed in the later Cretaceous of the western interior region of the United States. It is estimated that fully 100,000 square miles are underlain with chiefly lignitic and bituminous coals as well as a little anthracite coal. Considerable Cretaceous coal also occurs in Australia and New Zealand.

The greensands (glauconitic) of the Atlantic Coastal Plain, especially in New Jersey and Virginia, were formerly extensively used as land fertilizers on account of their phosphoric acid content.

A heavy production of petroleum has been obtained from the Cretaceous strata of Texas, particularly in the vicinity of Beaumont. Both oil and gas are obtained from the Cretaceous in Louisiana and Wyoming.

Cretaceous limestones are quarried in Kansas, Nebraska, and Iowa for building stone.

The most important sulphur deposits in the United States occur in rocks of Cretaceous age in Louisiana.

The vast supply of underground water obtained from the Cretaceous (Dakota) sandstone in the Great Plains region is worthy of special mention. Much artesian water is also derived from Cretaceous beds in the Atlantic and Gulf Coastal Plain. In the regions just mentioned the water is held under pressure in porous sandstone by overlying impervious clay or shale.

Life of the Cretaceous

Plants. — Early in the period the plants were very much like those of the preceding Mesozoic periods, the dominant types still having been *Ferns*, *Equisetæ*, *Cycads*, and *Conifers*.

Among the *Gymnosperms*, which were distinctly subordinate and a good deal like those of the present day, a feature of special interest was a considerable development of the genus *Sequoia*

which is still represented by the so-called "Big Trees" and giant Redwoods of California.

Before the Cretaceous, *Angiosperms* are not definitely known to have existed, but in North America there can be no possible doubt of their presence — both Monocotyledons and Dicotyledons — even in late Lower Cretaceous time. By the close of the period the Angiosperms had developed so phenomenally as to attain a position of supremacy among plants, which position they have maintained ever since. This comparatively sudden appearance and remarkable development of the Angiosperms "was one of the most important and far-reaching biologic events the world has known. . . . So far as we know, this flora appears to have had its origin in eastern or northeastern North America, in the Patapsco division of the Potomac series. Although the great majority of the plants found in association in these beds, both as regards species and individuals, still belonged to lower Mesozoic types, such as Ferns, Cycads, and Conifers, we find ancient if not really ancestral Angiosperms. . . . No sooner were they (Angiosperms) fairly introduced than they multiplied with astonishing rapidity and in the . . . Raritan they had become dominant, the Ferns and Cycads having mostly disappeared and the Conifers having taken a subordinate position." [1]

Fig 183

Cretaceous Foraminifers, greatly enlarged (After Calvin, from Le Conte's "Geology," permission of D Appleton and Company)

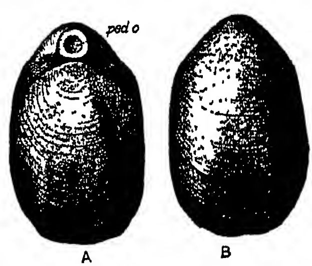


Fig. 184

A Cretaceous Brachiopod, *Terebratula harlani*. Note the curved hinge line. (From Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company)

[1] F. H. Knowlton: In *Outlines of Geologic History*, by Willis and Salisbury, pp 205–206.

a *b* *c*

Fig. 185

Typical Cretaceous Pelecypods: *a, Ostrea diluviana* (Hill and Vaughan); *b, Exogyra ponderosa* (L. W. Stephenson); *c, Inoceramus labiatus* (Darton). (All from U. S. Geological Survey.)

No present-day species existed, but, among the more modern genera were Oaks, Elms, Magnolias, Maples, Figs, Laurels, Palms, Grasses, etc. Later Cretaceous Angiosperms were remarkably uniform and widespread over the earth.

Lower Invertebrates. — The lower forms of Cretaceous Invertebrates were largely, except in detail, much like those of the present day. Special mention may be made of the *Foraminifers* which were perhaps more prolific than during any other period. Their tiny shells practically make up the great chalk beds, especially those of England, France, and the Gulf Coast of the United States.

Mollusks. — *Pelecypods* continued to be very abundant, with the same genera of the *Oyster* (*Ostrea*) family of the two preceding periods still prominent. In addition to these were many species of the characteristic genera Exogyra and Inoceramus (see Fig. 185). Many of the other genera, often of modern aspect, were also present.

Gastropods were enriched by the appearance of many modern genera.

Cephalopods. The *Nautiloids* had before this become greatly reduced, with only a comparatively few coiled forms of rather modern aspect left. *Ammonoids* continued to be very prominently represented as regards both numbers of species and individuals, especially by the *Ammonites*, of which thousands of species are known from the Mesozoic alone. Some Cretaceous Ammonites attained a diameter of several feet. During the Cretaceous many of the Ammonites showed a remarkable tendency to assume strange forms (Fig. 186). Some developed uncoiled shells; others spiral shapes, while still others were curved or actually straight (e.g. *Baculites*). Thus, externally at least, there was a reversion to the early Paleozoic forms, but in all cases they retained their complicated suture or partition structure. "These strange forms have been likened by Agassiz to death-contortions of the Ammonite family; and such they really seem to be. . . . From the point of view of evolution, it is natural to suppose that under the gradually changing conditions which evidently prevailed in Cretaceous times, this vigorous Mesozoic type would be compelled to assume a great variety of forms, in the vain attempt to adapt itself to the new environment, and thus to escape its inevitable destiny. The curve of its rise, culmination, and decline

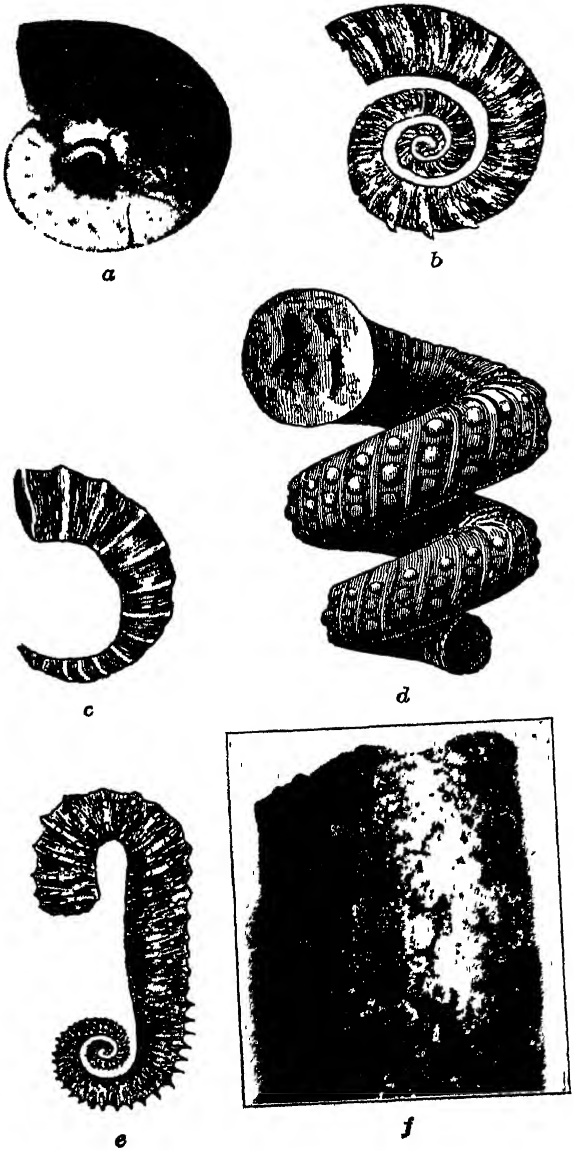


Fig 186

Typical Cretaceous Ammonites. *a*, *Placenticeras intercalare* (Meek), *b*, *Crioceras duvali*, *c*, *Toxoceras bituberculatum*; *d*, *Helioceras robertianus* after Pictet); *e*, *Ancyloceras matheronianum*; *f*, *Baculites ovatus*, with outer shell removed to show sutures. (*d*, from Le Conte's "Geology," courtesy of D. Appleton and Company; *f*, photo by the author)

reached its highest point just before it was destroyed The wave of its evolution crested and broke into strange forms at the moment of its dissolution."[1] Very few if any Ammonites crossed the line into the early Cenozoic, and such an abrupt termination of so abundant and diversified a group of animals has rarely been equaled in the history of the animal kingdom. *Belemnites* still were abundant and these, too, showed a remarkable decline by the close of the Cretaceous.

Arthropods. — Broadly considered, the Cretaceous Arthropods were much like those of the Jurassic, though the short-tailed

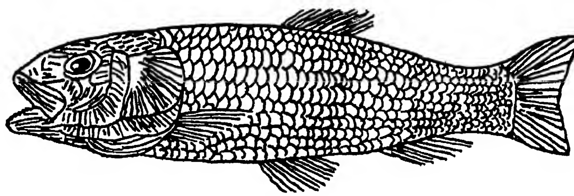


Fig 187

A Cretaceous Teleost Fish, *Osmeroides Lewesiensis*, restored

Decapods (Crabs) increased notably. Most of the Arthropods were of rather modern aspect, though the species were quite different from those of today.

Fishes. — From the standpoint of evolution, a very important change took place among the Fishes. *Sharks* were common, having left an almost incredible number of fossil teeth. For the first time the *Teleosts* (typical bony Fishes), which were introduced in a small and primitive way in the Jurassic, predominated over the *Ganoids*. Many Cretaceous Teleosts belonged to families or genera which still exist, such as Salmon, Herring, Bass, Cod, etc. Other types were more characteristic of the time.

Amphibians. — These were of quite modern appearance and they occupied much the same relatively subordinate position that they do today.

Reptiles. — Most of the great characteristic groups of Jurassic Reptiles continued into the Cretaceous, while certain new forms, such as *Mosasaurs*, *Triceratops*, and *Snakes*, were added. Mesozoic Reptiles are discussed at the end of this chapter.

[1] J. Le Conte. *Elements of Geology*, 5th ed., pp. 499–500.

Birds. — During the long time between the Jurassic, when the first known Birds appeared, and the Upper Cretaceous, important evolutionary changes took place in this class of animals, though fossils of the interval are almost, if not wholly, absent. Cretaceous Birds were distinctly more advanced and modern in appearance than were those of the Jurassic. Thus the long, vertebrated tail of the earlier forms had become greatly shortened, and the only important primitive characteristic which they retained was the possession of teeth. Compared with modern Birds, they had much smaller brain cavities.

At least 30 species of Cretaceous Birds are known, all of these belonging to two great, though very different, groups (orders) e.g. *Ichthyornis* and *Hesperornis*. All appear to have been aquatic forms. The *Ichthyornis* types were powerful fliers, as proved by the strongly developed keel and wing bones. The teeth were set in distinct sockets. The structure (biconcave) of their vertebræ was quite distinctly reptilian. They averaged about the size of a pigeon (see Fig. 188).

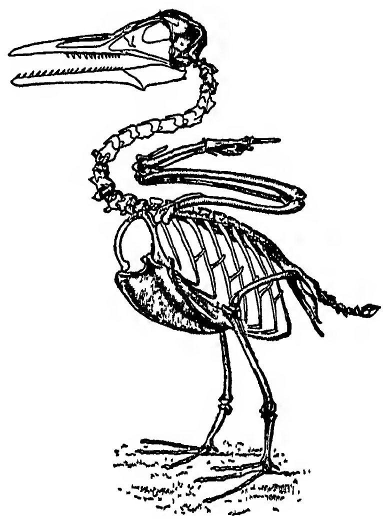


Fig. 188

A Cretaceous toothed Bird, *Ichthyornis victor* Height, about 9 inches (After Marsh.)

Hesperornis comprised forms incapable of flight, but often of great size — five to six feet in length. In marked contrast with the Ichthyornis, these forms had powerfully developed legs which served as swimming paddles in these almost wholly aquatic forms. In every way they were adapted to rapid swimming. Their teeth were set in grooves instead of sockets.

Mammals. — As in the earlier Mesozoic periods, the Cretaceous Mammals were small, primitive forms which still occupied a very subordinate position among the animals of the time. Before the end of the Cretaceous, however, "there were at least six groups of

these archaic Mammals in existence, including insect-eaters, carnivores, ancestral Monkeys or Lemurs, Rodents, and hoofed types. None were larger than sheep, the limbs were short, the tails long and heavy, and the brain exceedingly small. . . . From this small 'minority,' once the reptilian menace was removed, and the earth clad with grasses and cereals on which they could best feed, was to come a mammalian host that should exceed even that of the Reptiles in variety, and that was to develop brain instead of brawn until it culminated in Man."[1]

Mesozoic Reptiles

The Mesozoic era has been appropriately called the "Age of Reptiles," since those animals were at once the most characteristic and powerful creatures of the time So far as known, the first true Reptiles appeared in the Permian. During the Mesozoic they rose to great prominence, both in number of individuals and diversity and size of forms, reached their culmination in the midst of the era; and declined in a most remarkable manner toward the close of the era. During the Mesozoic the Reptiles ruled all fields — sea, land, and air.

"The advance from the Amphibian to the Reptile was a long forward step in the evolution of the Vertebrates. . . . Yet in advancing from the Amphibian to the Reptile the evolution of the Vertebrate was far from finished. The cold-blooded, clumsy and sluggish, small-brained and unintelligent Reptile is as far inferior to the higher Mammals, whose day was still to come, as it is superior to the Amphibian and the Fish" (W. H. Norton).

The Principal Extinct Mesozoic Reptile Groups

The following grouping of the more characteristic, extinct Mesozoic Reptiles is not meant to be an exact scientific classification, but rather it is a simple arrangement for convenience of elementary discussion. Unless otherwise stated the types mentioned ranged through the whole Mesozoic.

Enaliosaurs. — There are many known types of these swimming Reptiles, but only a few of the most typical and characteristic forms are chosen for description.

[1] C. Schuchert: *The Earth and Its Rhythms*, p. 311.

Fig. 189

A group of Ichthyosaurs, *Ichthyosaurus quadricissus*, of the Enaliosaur division of Mesozoic Reptiles. Maximum length 25 to 30 feet. Restoration by C. R. Knight, under the direction of H. F. Osborn. (By permission of the American Museum of Natural History.)

1. ENALIOSAURS ("Sea-lizards") (Swimming Reptiles) e.g.	1. Ichthyosaur ("Fish-lizard") 2. Plesiosaur ("Lizard-like"). 3. Mosasaur ("Meuse River lizard") (Later Mesozoic only).
2. DINOSAURS ("Terrible-lizards") (Walking Reptiles) e g	1. Sauropod ("Lizard-footed") (Not known from the Triassic) 2 Stegosaur ("Plated-lizard") (Not known from the Triassic) 3. Triceratops ("Three-horned face") (Later Mesozoic only) 4 Theropod ("Beast-footed") 5 Ornithopod ("Bird-footed") (Not known from the Triassic).
3 PTEROSAURS ("Winged-lizards") (Flying Reptiles). e g	1 Pterodactyl ("Winged-finger"). 2 Rhamphorhynchus ("Beaked-snout").

The *Ichthyosaurs* were Fish-like forms which ranged in length up to 25 or 30 feet. They had stout bodies, very short necks, and very large heads (see Fig. 189). The head, sometimes 4 or 5 feet long, had an elongated snout in which as many as 200 large sharp teeth were set in grooves (not in sockets). Enormous eyes, sometimes over a foot in diameter, were protected by bony plates. A powerful tail with two lobes set vertically had the vertebral column extending through the lower lobe. The four limbs were perfectly converted into swimming paddles, thus strongly suggesting that these, as well as other Enaliosaurs, represent former land Reptiles which adapted themselves to a water environment much like certain Mammals of today, such as Whales and Dolphins. Fishes and Cephalopods were largely their prey, as proved by the fossil contents of their stomachs, no less than 200 Belemnite remains having been found in one specimen alone. Many remarkably preserved specimens of Ichthyosaurs have been discovered (Fig. 190), some with even the embryos plainly visible within the bodies. Ichthyosaurs ranged through the whole Mesozoic.

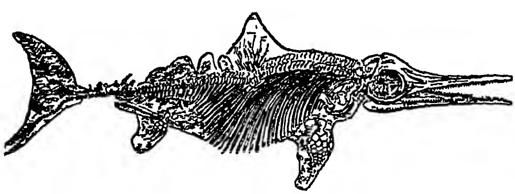


Fig 190

A well-preserved Ichthyosaur found in Germany. (After Fraas.)

Plesiosaurs were less powerful forms than Ichthyosaurs, though they were usually longer, some having attained a maximum length of 40 to 50 feet (Fig. 191). A stout body, long, slender neck, small head, short tail, and four powerful paddles were characteristic features. Sharp teeth were set in sockets (not grooves) in the jaw. With their slender, serpent-like necks, often 10 to 20 feet long, "the Plesiosaurs could lie motionless far below the

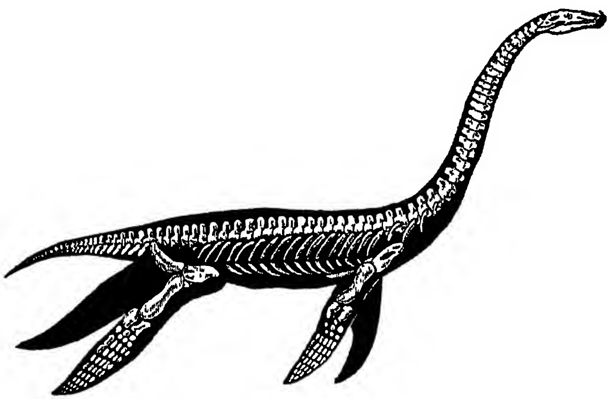


Fig 191

A restored Plesiosaur, *Plesiosaurus dolichodeirus*, of the Enaliosaur division of Mesozoic Reptiles. Maximum length 40 to 50 feet (From Le Conte's "Geology," courtesy of D. Appleton and Company)

surface, occasionally raising their heads above the water to breathe, or darting them to the bottom after their prey, which consisted chiefly of Fish" (W. B. Scott). Plesiosaurs ranged through the whole Mesozoic.

Mosasaurs were literal "sea-serpents" or carnivorous marine Reptiles which often reached a length of from 40 to 75 feet (Fig. 192). Though now wholly extinct, they were closely related to Snakes and Lizards in structure. The four limbs were converted into short, stout, swimming paddles, and their jaws were set with sharp teeth. The relatively smaller head, long, slender body, and different tail structure distinguish the Mosasaurs from the Ichthyosaurs, as a comparison of the accompanying pictures will show. Mosasaurs existed during the latter portion only of the Mesozoic.

Dinosaurs. — These Mesozoic Reptiles comprised a great variety of forms as regards both shape and size. Only five of the more common and characteristic types have been selected for description. Like most other Reptiles, the Dinosaurs laid eggs, fossilized specimens of which have been found.

The *Sauropods* were the largest of all Mesozoic Reptiles, and in fact they included the largest animals which ever trod the earth.

Fig 192

A Mosasaur, *Tylosaurus dyspelor*, of the Enaliosaur division of Mesozoic Reptiles. Maximum length about 75 feet. Restoration by C. R. Knight under the direction of H F. Osborn. (Courtesy of the American Museum of Natural History, from Scott's "Geology," by permission of The Macmillan Company)

Well-preserved specimens are known whose lengths are from 75 to 90 feet, and recently one has been discovered in Utah which it is thought will, when mounted, show a length of over 100 feet. It has been estimated that one of these large brutes must have weighed about 40 tons. Note the extremely long neck and tail, very small head, and strong bones of the four great legs. Thigh bones 7 feet long are known. They were five-toed and plantigrade, and doubt-

less walked with body well above ground (Fig. 193). All were plant-eaters and provided with grinding teeth. Sauropods ranged through all the Mesozoic except the Triassic.

The *Stegosaurs* are so named because of the double row of great bony plates on the back of each of these most remarkable brutes (Fig. 194) which attained a maximum length of 30 to 40 feet. The long, powerful tail had several pairs of long spines toward the end

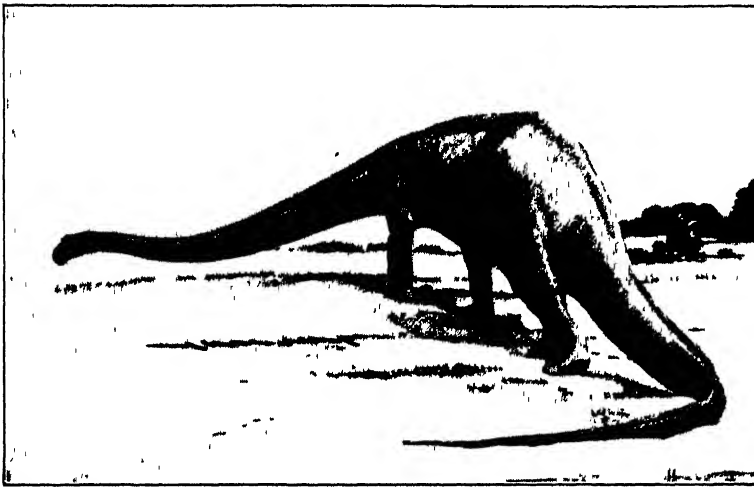


Fig 193

The hugest of all known Dinosaurs, a Sauropod, *Diplodocus*. A mounted skeleton in the Carnegie Museum of Pittsburg measures 87 feet long Restored by C. R. Knight under the direction of H F. Osborn (Courtesy of the American Museum of Natural History)

instead of plates. As compared with the Sauropods the neck was short. They were quadrupedal, four-toed in front, and three-toed in the rear. All were plant-eaters. The brains of all Dinosaurs were almost incredibly small, even as compared with modern Reptiles, and "this was especially true of Stegosaurs. To make up for this deficiency they had an enormous enlargement of the spinal cord in the sacral region (i.e. over the hind leg). This sacral brain — if we may so call it — was ten to twenty times bigger than the cranial brain. It was necessary in order to work the powerful hind-

Fig 194

A Stegosaur, an armored Dinosaur. Maximum length 30 to 40 feet. Restored by C R Knight. (By permission of F A. Lucas and Doubleday, Page and Company, and courtesy of Henry Holt and Company)

legs and tail" (J. Le Conte). Stegosaurs existed through all of the Mesozoic except the Triassic.

Triceratops was another strange-looking creature, so named because of its three horns—two of great size just back of the eyes and

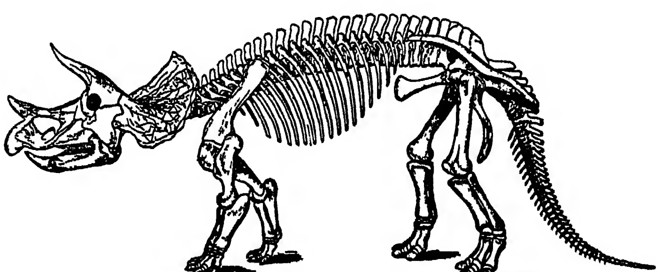


Fig. 195

A Triceratops, *Triceratops prorsus*, of the Dinosaur division of Mesozoic Reptiles. Maximum length 25 feet (Skeleton restored by Marsh.)

a smaller one on the nose (see Fig. 195). The enormous flattened skull had a sharp beak in front. The skull extended backward into an immense hood or cape-like structure. According to Marsh they (Triceratops) had the largest heads and smallest brains of the Reptiles, and hence they must have been exceedingly stupid. Skulls 6 or 8 feet long have been found. The four legs and the tail were massive and powerful. This creature attained a length of fully 25

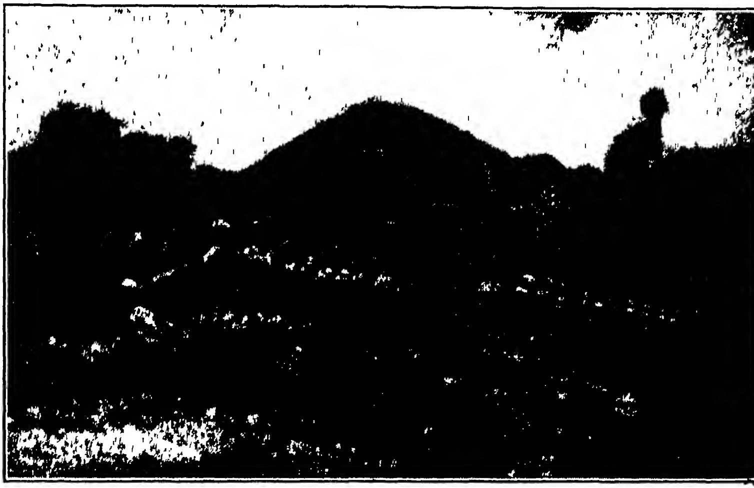


Fig. 196

Theropods, *Allosaurus agilis*, of the Dinosaur division of Mesozoic Reptiles Restored by C. R. Knight, under the direction of H. F. Osborn. (Courtesy of the American Museum of Natural History.)

feet, and it had a bulk about twice that of an Elephant. It was a plant-eater and probably not as ferocious as it looked. Good specimens have been found in the western interior of the United States. Triceratops existed only during the Cretaceous period.

Theropods were carnivorous Dinosaurs, as proved by their numerous sharp teeth set in comparatively large heads (see Fig. 196). They were bipedal, that is they walked on two legs, the front limbs having been very small and used only for grasping. The toes were armed with sharp claws. The bipedal habit combined with the long, ponderous tail gave them a sort of Kangaroo

aspect. The limb bones were hollow, thus suggesting a bird-like structure. In fact before it was known that the numerous tracks in the Newark sandstone of the Connecticut Valley were made by creatures of this sort, they were called "Bird-tracks." Theropods varied in length from 4 to over 40 feet, and though much smaller than many other Dinosaurs, they were probably the most ferocious of all and more than likely preyed upon the much larger plant-eaters. A mounted skeleton of one of these creatures, called *Tyrannosaurus*, in the American Museum of Natural History is

Fig. 197

Dinosaur eggs weathering out of a cliff of Cretaceous strata in Mongolia (Courtesy of the American Museum of Natural History.)

47 feet long. It represents the greatest known flesh-eating land animal of all time. The Theropods lived through the whole Mesozoic, and they have been found in many parts of the world.

Ornithopods were in general appearance much like the Theropods, but they were certainly plant-eaters, as shown by the tooth structure. They were bipedal, the hind limbs having only three functional toes, giving a sort of bird-like track. The largest of these creatures measured 30 feet in length, and when walking they must have stood 15 or 20 feet high. Ornithopods ranged through all the Mesozoic except the Triassic.

Pterosaurs. — These were literal "flying-dragons" in Mesozoic time. They varied greatly in size from about that of a

Fig. 198

Unearthing Dinosaur bones in Bone Cabin Quarry, Wyoming. (Courtesy of the American Museum of Natural History)

sparrow to others with a spread of wing of 25 feet, which is about twice that of any modern Bird. Not only did they include the largest creatures which ever flew but, on account of their hollow bones, their skeletons were wonderfully light. One finger of each front limb was enormously lengthened to support the flying membrane, as shown in Fig. 199. The other fingers were armed

Fig. 199

A Rhamphorhynchus of the Pterosaur division of Mesozoic Reptiles. Spread of wing about 2 feet. (Restored by Marsh.)

with sharp claws. In general we may recognize two groups. One group was typified by the *Pterodactyl*, which had a short, stout body, short tail, and moderately long neck. The earlier Mesozoic forms were supplied with sharp teeth, while the Cretaceous forms were mostly toothless. The other group, typified by the *Rhamphorhynchus* (Fig 199), had long tail, and in one species at least the end of the tail was expanded into a sort of rudder. Many wonderfully preserved specimens of Pterosaurs have been found, some with even the wing membranes preserved. Pterosaurs ranged from the late Triassic to the close of the Mesozoic.

The Principal Surviving Mesozoic Reptile Groups

Though overwhelmed by the Reptiles above described and of less peculiar interest because they represent groups still living, certain other Mesozoic Reptiles deserve brief mention.

Turtles date back at least to the middle Triassic, and even those very early forms clearly showed the familiar structure which easily separates them from other Reptiles.

Lizards are known even from the Triassic, and, though they ranged through the Mesozoic, they were always small and comparatively rare.

Crocodiles made their first appearance in the Jurassic, and some were marine forms. In appearance they resembled the modern Gavial of India, particularly as regards the long, slender snout. Crocodiles were numerous from the Jurassic to the end of the Mesozoic.

Snakes are not known to have appeared till late in the Cretaceous, and those early forms were small and comparatively rare.

CHAPTER XVII

SUMMARY OF MESOZOIC HISTORY

Although the Mesozoic was quite certainly shorter than the Paleozoic, it must, nevertheless, have had a duration of at least some millions of years. As the name indicates, the Mesozoic was the era of transition between the Paleozoic and the Cenozoic. Eastern North America had been to a large degree completed at the time of the Appalachian Revolution, except for the addition of the Atlantic and Gulf Coastal Plain belts. In western North America, however, profound physical geography changes took place, bringing that part of the continent almost to its present condition, as regards relations of land and sea, only near the close of the Mesozoic. The life of the Mesozoic, too, was distinctly intermediate in character, those of the great groups of characteristic Paleozoic organisms which did continue into the Mesozoic having become extinct during the era, while many more modern groups showed great development during the era. Certain other important groups of organisms like the Cycads, Ammonites, and Reptiles, were eminently characteristic of the Mesozoic and reached their culmination during the era.

Mesozoic Rocks

The late Triassic stratified rocks of the Atlantic Coast are sandstones, conglomerates, and shales, mostly of continental origin, though in part at least probably of estuarine origin. Rocks of the Triassic in the western interior are chiefly the Red Beds (shales, sandstones, and limestones), with more or less salt and gypsum, of terrestrial or lacustrine origin. On the Pacific Coast the strata are of true marine origin and they consist of all sorts of typical sediments.

Jurassic strata are wholly confined to the western interior and Pacific borders, where they are all typical marine sediments, except the earlier Jurassic beds of the western interior, which are of continental origin and probably also include some Red Beds.

Lower Cretaceous strata occur on the Atlantic and eastern Gulf coasts, where they consist almost entirely of unconsolidated sands and clays of continental origin. The Lower Cretaceous strata in the Texan region are made up chiefly of more or less consolidated sands, sandstones, and chalky limestones of marine origin, with continental deposits at the base In the western interior regions of both the United States and Canada, the strata rather doubtfully of this age are probably of continental origin. On the Pacific Coast there are great thicknesses of marine Lower Cretaceous strata.

Upper Cretaceous deposits of the Atlantic and eastern Gulf regions are mostly sands, clays, marls, and greensands, with some chalky limestones toward the south. These are very largely of marine origin. In Texas and the western interior the Upper Cretaceous beds are there mostly marine sandstones, shales, and chalky limestones, though some continental deposits (including coal) also occur, especially in the latest Cretaceous. On the Pacific Coast typical marine beds occur.

Some igneous rocks, both volcanic and intrusive, occur in the Atlantic Coast Triassic. Large quantities of volcanic rocks of Triassic and Jurassic ages, and some of Cretaceous age, occur on the Pacific Coast, especially in British Columbia. Tremendous masses of Late Jurassic granite and diorite occur on the Pacific, particularly in the Sierra Nevada Mountains and in the mountains of southern California.

In general the thickness of the Mesozoic group of rocks is not nearly as great as that of the Paleozoic, but more locally remarkable thicknesses of strata are represented in even single systems, as in the case of the Triassic beds of the Atlantic border (10,000 to 15,000 feet thick), or the Lower Cretaceous beds of the Pacific border (fully 26,000 feet thick).

Physical History

Relations of Land and Sea. — Throughout the era, except during parts of the Cretaceous, North America was very largely dry land, thus being in marked contrast with the Paleozoic condition of the continent. The eastern half or two-thirds of the continent, except the Atlantic and Gulf borders during part of the Cretaceous, was continually dry land, while the western part of

the continent was subject to varying marine, estuarine, lacustrine, and desert-basin conditions. The reader should review the paleogeographic maps.

Early in the Mesozoic era, or Triassic period, eastern North America was all dry land; continental and some marine deposits were forming in the western interior of the United States; and the Pacific border was mostly occupied by marine waters. Later in the Triassic the same conditions prevailed in the west, but long, narrow troughs were formed along the Atlantic side in which were deposited the thick continental and estuarine (Newark) deposits. At the close of the Triassic, or beginning of the Jurassic, there was enough crustal movement to convert the basins (Newark) of deposition in the east into dry land, while on the Pacific Coast the sea withdrew, thus leaving the whole continent land

During the Jurassic the Pacific Coast again showed a strong tendency to be submerged, and in the later Jurassic a transgression of the sea took place from Alaska southward over the Rocky Mountain region as far as central Arizona. During the whole Jurassic eastern North America was land, and at the close of the period the whole continent was land.

During the Lower Cretaceous there was enough subsidence of the Atlantic and eastern Gulf borders to produce flood-plains, lakes, and marshes in which were deposited the Potomac series of sands, gravels, clays, etc. About the same time the continental (Trinity) deposits, followed by the marine Fredericksburg and Washita beds, were accumulating over the western Gulf (Texan) regions and southern western interior regions, and continental deposits were forming over the northern western interior region just west of the site of the Rockies. During the Lower Cretaceous on the Pacific border there accumulated very thick marine deposits just west of the newly formed Sierra Nevada, especially in the Great Valley of California. Marine deposition also took place along much of the coast north of California.

The Lower Cretaceous closed, or the Upper Cretaceous opened, with the eastern part of the continent all undergoing erosion; a general submergence of the western Gulf (Texan) and southern western interior regions; and considerable deformation and uplift of the strata in parts of the Coast Range district.

At the opening of the Upper Cretaceous the condition of the continent was essentially that just described for the close of the

TABULAR SUMMARY OF MESOZOIC LIFE

	Plants	*Protozoans*	*Porifers and Cœlenterates*	*Echinoderms*
CRETACEOUS	Cryptogams and Gymnosperms Much like earlier Mesozoic Angiosperms Monocotyledons and Dicotyledons attain supremacy among plants	Foraminifers and Radiolarians Profuse	Sponges and Corals Abundant and much like those of the Jurassic	Crinoids Greatly reduced Asterozoans Present Echinoids Both regular and irregular forms common
JURASSIC	Cryptogams Much like Triassic Gymnosperms Cycads culminate, Conifers more modern in aspect	Foraminifers and Radiolarians Very abundant and highly diversified	Sponges Very abundant Corals Abundant and all are Hexacoralla of modern appearance	Crinoids Very profuse and notably large Asterozoans Present and of modern appearance Echinoids Abundant, with first irregular, more modern forms.
TRIASSIC	Thallophytes Bryophytes Pteridophytes Lycopods almost extinct, Ferns and Equisetæ common Gymnosperms Cordaites become extinct, Cycads and Conifers prominent	Foraminifers and Radiolarians· Present	Sponges· Present Corals Very abundant, especially the more modern Hexacoralla, ancient Tetracoralla become extinct	Crinoids· Common Asterozoans Present Echinoids Common and all are regular forms of ancient aspect

Lower Cretaceous. Early in the Upper Cretaceous, marine waters spread over practically all of the Atlantic and eastern Gulf Coastal Plain areas. At the same time "Appalachia," which had been so long persistent, became submerged. The Texan and western interior areas were marked by the deposition of the marine sandstone early in the period. At the same time the western edge of the continent was submerged under the sea.

In middle Upper Cretaceous time, the Atlantic Coast and eastern Gulf districts continued much as in the earlier Upper Cretaceous. The western Gulf and western interior districts, however, were marked by a vast transgression of the sea from the Gulf to the Arctic, while the Pacific border continued as earlier in the

TABULAR SUMMARY OF MESOZOIC LIFE — *Continued*

Molluscoids	*Mollusks*	*Arthropods*	*Vertebrates*
Bryozoans Present Brachiopods Only a few genera and species remain, and these are of rather modern aspect	Pelecypods and Gastropods Abundant and similar to Jurassic, but more modern Cephalopods Still very abundant and much like those of the Jurassic with uncoiled to even straight Ammonoids (e g Baculites) common Ammonoids and Belemnites become extinct Dibranchs common	Eucrustaceans Much like Jurassic, but Brachyurans (Crabs) greatly increased Insects Much like Jurassic but even more modern types appear	Fishes Selachians abundant, Dipnoans rare, Ganoids common, Teleosts predominate Amphibians Very subordinate Reptiles· Abundant, but Enaliosaurs, Dinosaurs, and Pterosaurs become extinct Snakes appear Birds Much increased Mammals Simple, rare
Bryozoans Present Brachiopods Still more diminished and not many species	Pelecypods Similar to Triassic, but increased Gastropods Ditto Cephalopods· Nautiloids of coiled forms only and common, Ammonoids (e g Ammonites) culminate, with development of some uncoiled to even straight forms, Dibranchs become profuse (e g Belemnites)	Eucrustaceans Macrurans (e g Lobsters) common, and Brachyurans (e g Crabs) first appear, though rare Insects Abundant and diversified, first appearance of highest forms, e g Flies, Butterflies, Ants and Bees	Fishes Selachians common, Dipnoans rare, Ganoids common, Teleosts first appear, but rare Amphibians· Fossils? Reptiles: Much like Triassic, but more common and varied Birds First appear (e g Archeopteryx) Mammals Simple, rare
Bryozoans Present. Brachiopods Greatly diminished and those with curved-hinge lines prevail for the first time.	Pelecypods and Gastropods Prominent and assume more distinctly modern aspect Cephalopods· Nautiloids common, with straight forms (Orthoceras) becoming extinct, Ammonoids common, with complex sutures (e g Ceratites and Ammonites), Dibranchs first appear.	Eucrustaceans Macrurans (e g Lobsters) first appear. Insects Common and mostly simpler forms but first Beetles appear.	Fishes. Selachians, Dipnoans and Ganoids much as in late Paleozoic time Amphibians Declining but large Reptiles Abundant and varied, e g Enaliosaurs, Dinosaurs, and Pterosaurs, first Turtles and Lizards Mammals. First and rare

Upper Cretaceous. In very Late Cretaceous time there was a general withdrawal of the sea.

Mountain Making. — The Jurassic period was closed in the west by the "Sierra Nevada Revolution," when strata of great thickness were folded into mountains along the present site of the Sierra Nevada, and probably also the Cascades. There was also some deformation in the region of the Coast Ranges.

The Mesozoic era was closed by one of the most profound physical disturbances in the post-Proterozoic history of North America, if not in the world, — the "Rocky Mountain Revolution," — when strata were more or less deformed by folding and faulting throughout much of the Rocky Mountain system. At

the same time the whole eastern side of the United States, including the Appalachians, which had been worn down to a peneplain, was distinctly upraised without renewed folding of the rocks.

Igneous Activity. — While the later Triassic (Newark) sandstones were forming on the Atlantic Coast, there were considerable intrusions and extrusions of igneous rocks, now represented by such masses as the Palisades of the Hudson and the Holyoke Range of Massachusetts.

Great masses of plutonic igneous rock were intruded during Late Jurassic time as an accompaniment of the Sierra Nevada Revolution, and there was much volcanic activity from northern California to Alaska during Mesozoic time.

Accompanying the Rocky Mountain Revolution there were tremendous outpourings of lava in the western portion of the continent.

Climate

The character and distribution of organic remains, both plant and animal, rather clearly prove the climate of the Mesozoic to have been mild to possibly even warm temperate, with an appreciable distinction of climatic zones, though not at all comparable to those of the present. Warm temperate plants of the Cretaceous are found even within the Arctic circle.

In early Mesozoic time arid climate conditions must have prevailed over the western interior of the United States, as shown by the Red Beds with some salt and gypsum.

There is no good evidence of glaciation in the Mesozoic.

Organic History

"The life of the Mesozoic constitutes a very distinctly marked assemblage of types, differing both from their predecessors of the Paleozoic and their successors of the Cenozoic. In the course of the era the plants and marine invertebrates remain throughout the era very different from later ones. Even in the Vertebrates, however, the beginning of the newer order of things may be traced."[1]

Among plants the Ferns, Cycads, and Conifers predominated during the earlier Mesozoic, but later in the era the Angiosperms,

[1] W. B. Scott. *Introduction to Geology,* 2nd ed , p. 655.

including both Monocotyledons and Dicotyledons, first appeared and very soon predominated.

Among animals the absence of certain characteristic Paleozoic groups should be noted, such as Cystoids, Blastoids, Trilobites, and Eurypterids. Other Paleozoic groups continued into the early Mesozoic and then either became extinct or very greatly diminished such as the ancient Corals (Tetracoralla), Brachiopods, Orthoceras, and Amphibians. Some of the more important groups which made their first appearance in the Mesozoic era and developed notably were modern Echinoids (e. g. Sea-urchins), modern Eucrustaceans (e g Lobsters and Crabs), highest Insects, Teleost Fishes, primitive Birds, and small, primitive Mammals. Reptiles, which began in the very late Paleozoic, developed marvellously during the era, thus justifying the application of the term "Age of Reptiles" to the Mesozoic.

As was the case toward the close of the Paleozoic era, so the mighty crustal disturbances of mountain-making and general uplift which affected many portions of the earth in late Mesozoic and early Cenozoic time produced profound changes in the natural environment, which in turn caused important changes in the organic world. The rule of the mighty Enaliosaurs, Dinosaurs, and Pterosaurs gave way to the reign of the more intelligent Mammals; Angiosperms dominated the plant world; Belemnites, the marvelous group of Ammonoids, and the toothed Birds disappeared; the highest types of Insects appeared; and Teleosts prevailed among the Fishes.

On the accompanying chart the author has brought together in concise form the salient facts regarding the life of the Mesozoic. In regular order, the principal successive changes in the subkingdoms and classes of plants and animals are graphically represented.

CENOZOIC ERA

CHAPTER XVIII

THE TERTIARY PERIOD

Origin of Name, Subdivisions, Etc.

The Cenozoic era is often called the "Age of Mammals" because, for the first time, these most highly organized of all animals became abundant and diversified and were masters of the land. Plants and animals both took on a decidedly modern aspect, with species of living organisms represented for the first time, some even in the early Cenozoic and many during the later portion of the era.

The name "Tertiary" has entirely lost its original significance, but has, nevertheless, become thoroughly fixed in the literature of geology. In the early days of the science, the whole known geological column was divided into three groups of rocks, and later into four groups, namely: Primary, Secondary, Tertiary, and Quaternary. After the discovery of rocks still older than these, the term *Primary* was replaced by Paleozoic; *Secondary* by Mesozoic; while *Tertiary* and *Quaternary* have been retained as subdivisions of the Cenozoic.

Following are the subdivisions of the Tertiary system now recognized as world-wide in application:

Tertiary System	Pliocene series ("More recent").	Upper Tertiary.
	Miocene series ("Less recent")	
	Oligocene series ("Little recent").	Lower Tertiary.
	Eocene series ("Dawn of recent").	

Sir Charles Lyell first divided the Tertiary into Eocene, Miocene, and Pliocene on the basis of percentage of living species represented in each series, there being very few in the earliest and a

very large percentage in the latest series. Later the Oligocene was added by combining some of the uppermost Eocene with some of the lowermost Miocene, though in North America the term Oligocene has been but little used till very recently, and even now such strata are not always separately differentiated.

Following are some of the principal subdivisions of the Tertiary as now recognized in various parts of the United States:

	TERTIARY SYSTEM			
	UPPER TERTIARY		LOWER TERTIARY	
	Pliocene	*Miocene*	*Oligocene*	*Eocene*
Middle Atlantic Coastal Plain	Lafayette (Pliocene?) Waccamaw	Chesapeake: Yorktown St. Marys Choptank Calvert	Not exposed north of South Carolina	Castle Hayne Trent Nanjemoy Aqua
Gulf Coastal Plain	Citronelle Caloosahatchee (Florida only)	Jacksonville and Choctawhatchee (Florida) Pascagoula (Alabama) Oakville (Texas)	Apalachicola Vicksburg	Jackson Claiborne Wilcox Midway
Western Interior	? Blanco Republican River	Loup Fork Florissant Arikaree	John Day White River	Uinta Bridger Green River Wasatch Wind River
Southern California	Fernando: Saugus Pico	Modelo (Puente) Topanga Vaqueros	Sespe	Tejon Meganos Martinez

Exact correlations of the various formations in these widely separated regions are not meant to be implied in the above table. Also these sets of strata contain various unconformities.

Distribution and Character of the Rocks

General Distribution. — Lower Tertiary (Eocene and Oligocene) strata appear at the surface in North America over the areas indicated on map Fig. 200. Disregarding the countries south of

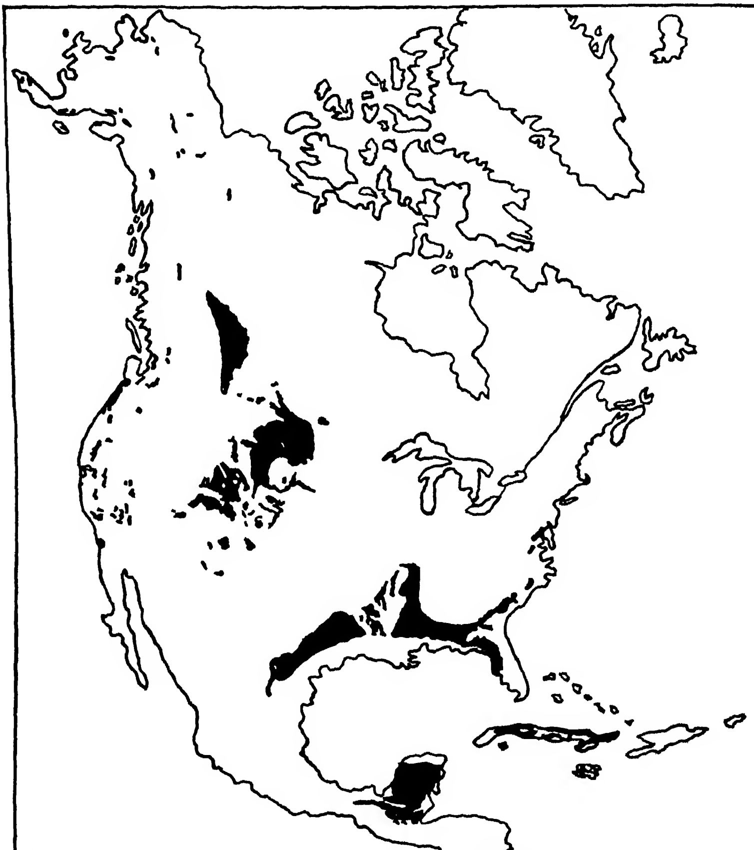


Fig. 200

Map showing the surface distribution (areas of outcrops) of Lower Tertiary (Eocene and Oligocene) strata in North America Tertiary lavas are separately shown on map figure 219. (Modified by W. J. M. after Willis, U. S. Geological Survey.)

the United States, there are, in general, four regions: Atlantic and Gulf Coastal Plain; western interior; Pacific Coast; and Alaska. The discontinuity of the areas on the Atlantic and Gulf Plain, especially the former, is due to the fact that later deposits overlap and conceal the Lower Tertiary strata in places. The Lower Tertiary strata extend oceanward or Gulfward under much or all of the Coastal Plain. In the western interior the numerous disconnected areas are chiefly due either to deposition in separate basins or removal of the strata from some places by erosion. On the Pacific Coast, Lower Tertiary strata appear mostly as small, narrow belts, because only the eroded edges of the upturned and folded rocks are visible in the mountains. Such strata are in reality much more extensively developed than these surface areas seem to indicate. There is no evidence that Lower Tertiary strata were deposited over any other parts of the continent than those above mentioned.

Upper Tertiary (Miocene and Pliocene) strata show a surface distribution as indicated on map Fig. 201. In general this distribution is much like that of the Lower Tertiary. On the Atlantic and Gulf Coastal Plain, it is quite the rule that the Upper Tertiary beds form a somewhat discontinuous belt between the continental margin and the belt of Lower Tertiary beds. Upper Tertiary strata are more extensive at the surface than Lower Tertiary on the Atlantic Coast and less extensive on the Gulf Coast. The margin of the continent, as well as much of Florida, are occupied by Quaternary deposits which are, mostly at least, underlain by the Upper Tertiary. In the western interior a large, nearly continuous area extends from northern Texas into South Dakota. The comparatively small, disconnected areas in the northwestern United States mostly represent deposition in separate basins. On the Pacific border of the United States the Upper Tertiary outcrops extensively as long, narrow bands, due to the fact that usually only the edges of the upturned strata are exposed. In British Columbia and Alaska Upper Tertiary rocks are only slightly developed. It is not known that late Tertiary strata ever occupied any other portions of the United States or Canada than those above mentioned.

Atlantic Coastal Plain Strata. — Lower Tertiary (Eocene) strata are only slightly exposed to view, while those of Upper Tertiary (Miocene and Pliocene) age are extensively exposed in the

Atlantic Coastal Plain. All the formations, except possibly the Lafayette, are there of marine origin and usually very fossiliferous.

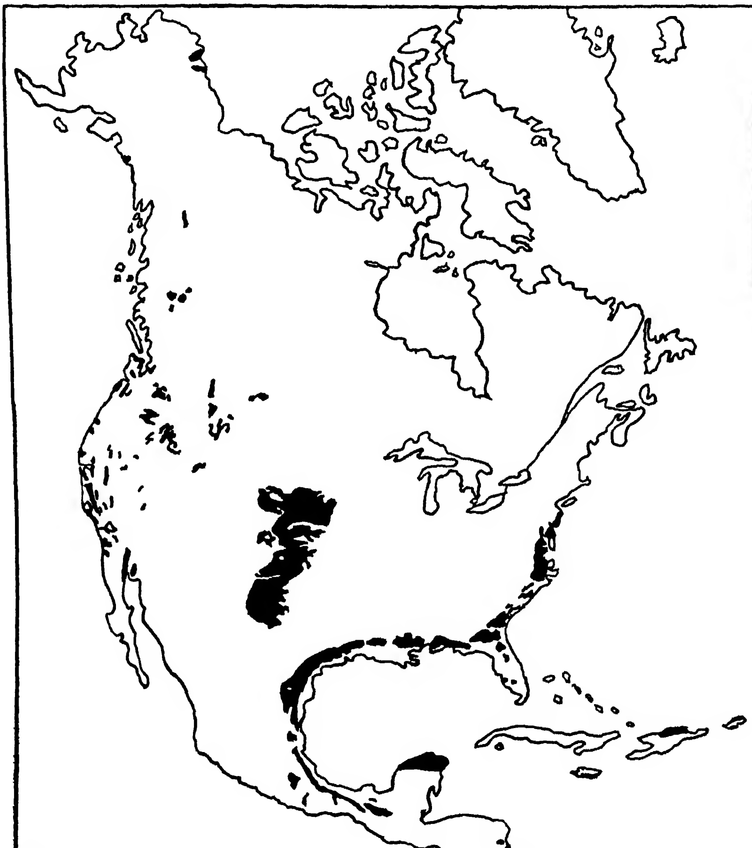


Fig. 201

Map showing the surface distribution (areas of outcrops) of Upper Tertiary (Miocene and Pliocene) strata in North America. (Modified by W. J. M. after Willis, U S. Geological Survey.)

The Eocene formations consist very largely of greensand marls and some clays. They show a maximum thickness of about 250 feet in Maryland and rest unconformably upon the older de-

posits. Oligocene strata have not been recognized north of South Carolina.

The Miocene beds are well developed, with a maximum thickness of nearly 500 feet. They are made up mostly of sands, clays, and marls.

The Pliocene is represented by the marine Waccamaw formation, which consists mostly of buff sands with some quartz pebbles

Fig. 202

Eocene sandstone resting by sharp contact upon Upper Cretaceous white chalk in Alabama. (After L W. Stephenson, U. S Geological Survey, Prof. Paper 90–J.)

and shell marls. The Pliocene is also thought to be represented by the problematical Lafayette formation (see below), which comprises sands, clays, loams, and gravels often rich in iron oxides. Its thickness seldom exceeds 50 feet. Lack of fossils makes it uncertain whether the formation is late Pliocene or early Pleistocene in age.

Gulf Coastal Plain Strata. — Here the Lower Tertiary (Eocene and Oligocene) strata are much more extensive at the surface than the Upper Tertiary. Both marine and non-marine deposits are present, with the former predominant.

The Eocene formations are much thicker (1700 feet maximum) than on the Atlantic Coast. Also the deposits are quite distinctly hardened into sandstones, shales, and limestones, with much lignite in some places.

The Oligocene is well represented by the *Vicksburg* limestone formation and the *Apalachicola* formation, which latter is very variable but mostly made up of limestones, marls, sands, and clays. These two formations are usually only a few hundred feet thick.

Miocene strata are represented in Florida by the *Jacksonville* limestone and *Choctawhatchee* marl, in the Alabama region by the *Pascagoula* bluish clay formation, and in Texas by the *Oakville* limestone formation. A maximum thickness of fully 1500 feet is attained in Texas.

The Pliocene is represented in Florida by the marine *Caloosahatchee* marl formation, but throughout the rest of the Gulf Coast the *Citronelle* formation appears to be the only representative of the Pliocene.

Western Interior-Great Plains Strata. — All Tertiary strata of the western interior are of non-marine origin, and they comprise lake, river, alluvial-fan, and wind deposits, with some volcanic ash and tuff (Fig. 203).

Of the Eocene deposits, the *Wind River* variegated shales, together with some sandstones and volcanic ash, are terrestrial (mostly fluviatile) deposits several hundred feet thick in Wyoming; the *Wasatch* variegated clays, shales, and sandstones, together with some coal, are very largely terrestrial deposits up to several thousand feet thick in Utah, western Colorado, and Wyoming; the *Green River* shales are lacustrine deposits just to the north and south of the Uinta Mountains; the *Bridger* beds, many hundreds of feet thick, are mostly volcanic dust, with some shales, etc., deposited partly on land and partly in shallow lakes in western Wyoming and northern Utah, while the *San Juan* formation, probably of the same age, is a great volcanic tuff deposit up to 2000 feet thick in Colorado; and the *Uinta* shales, sandstones, etc., are chiefly of terrestrial origin in western Wyoming, northeastern Utah, and northwestern Colorado.

Oligocene strata, represented by the *White River* formation of moderate thickness, occupy extensive areas in Wyoming, western South Dakota, western Nebraska, and eastern Colorado. The formation consists of clays and sandstones, with some limestone

and volcanic ash, variously deposited in lakes, by rivers, by wind, etc.

The *John Day* formation of eastern Oregon consists mainly of volcanic ash beds several thousand feet thick. It is rich in fossil land-animals.

The Miocene, far less thick than the Eocene, is represented

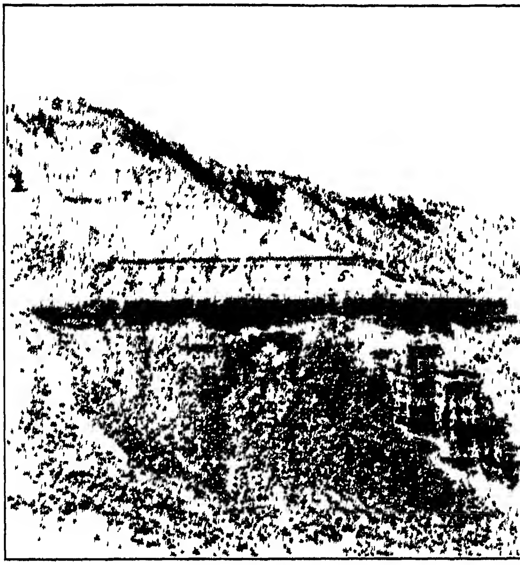


Fig. 203

Eocene-Oligocene strata as seen in the Wind River Basin of Wyoming. *3*, Eocene sandstone; *4*, *5*, *6*, *7*, Eocene sandstone and shale; *8*, *9*, Oligocene volcanic dust and marl. (After Sinclair and Granger, Amer. Mus. Nat. Hist., *Bul.* 30.)

toward the base by the *Arikaree* formation of chiefly soft sandstones some hundreds of feet thick in South Dakota, Nebraska, and Wyoming; toward the middle by the *Florissant* beds, which consist of laminated shales formed by deposition of fine volcanic ash in a small lake in Colorado and remarkable for the great number of insects and plants contained in it; and toward the top by the *Loup Fork* beds, which form thin deposits of fine sands and

marls (both subaërial and lacustrine) over extensive areas from South Dakota to Mexico.

Pliocene deposits formed in many parts of the western interior, but for most part they are difficult to separate from the later (Pleistocene) deposits. They are mostly of terrestrial origin, though probably with some lake deposits. Two formations which have been described as Pliocene east of the Rockies are the *Republican River* of Kansas and Nebraska, and the *Blanco* of northern

Fig 204

Nearly white, gently dipping Miocene (Modelo) shale on Mulholland Drive, Los Angeles, California Fossil Fishes occur at this locality. (Photo by the author.)

Texas and Nebraska. Other Pliocene deposits quite certainly occur west of the main axis of the Rockies.

In addition to the Tertiary beds above described in the western interior, there are also many small to large deposits, especially of Miocene and Pliocene ages, in the northwestern United States and the Great Basin between the Rocky and Cascade Mountains (see map Fig. 201). For most part these formations have not been carefully studied, though it is known that they represent all types of continental deposits.

Pacific Coast Strata. — Tertiary marine strata, together with some brackish and fresh water deposits, are extensively developed west of the Sierra Nevada and Cascades, and along the southern coast of Alaska.

Eocene strata are prominently developed in California, Oregon, Washington, and Alaska. They are mostly of marine and brackish

Fig 205

Soft white diatomaceous Miocene shale in southern California. (After Arnold, U. S. Geological Survey, *Bul* 322)

water origin and very thick (maximum 8000 to 12,000 feet). They are chiefly sandstones and shales, but with locally developed tuffs, conglomerates, and diatomaceous shales. Some Eocene strata of Alaska and Washington are of palustrine origin and contain coal.

Oligocene strata are much less widely distributed than the Eocene. The deposits are mostly sandstones and shales of marine origin in western Washington and Oregon, and in middle-western California. In southwestern California the *Sespe* formation is a non-marine red sandstone about 4000 feet thick.

Miocene marine strata are about as prominently represented on the Pacific Coast as the Eocene, the beds being very largely sandstones and shales, often with much diatomaceous shale, especially in the Upper Miocene (Fig. 205). The Miocene strata in California reach a maximum thickness of 15,000 to 20,000 feet, the *Modelo* formation alone being 9000 feet thick west of Los Angeles. Miocene is also well developed on the Pacific border of Alaska.

Pliocene marine strata are far less extensively developed on the Pacific Coast than the Miocene, the principal areas being in the

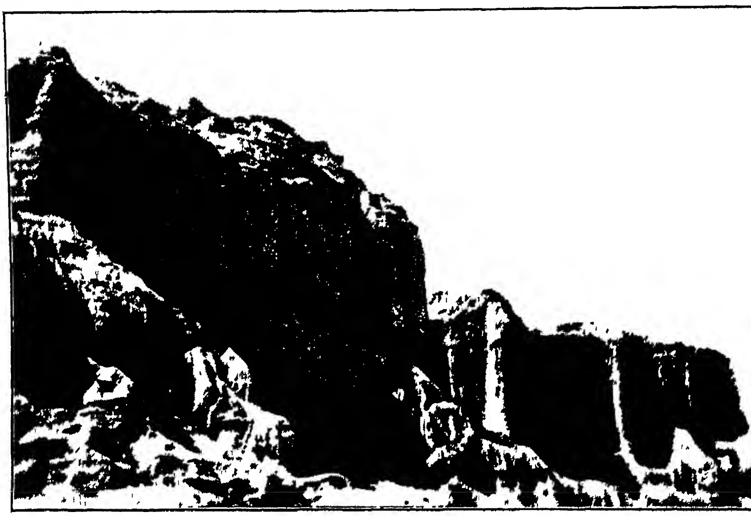


Fig 206

Soft volcanic tuff and shaly sandstone of late Tertiary age in Red Rock Canyon north of Mojave, California. The cliff, about 200 feet high, is remarkably sculptured by rain-wash. (Photo by the author.)

Coast Ranges of California, the southwestern border of California, and several small areas on the coast of Oregon and Washington. Pliocene fresh-water beds are widely developed in the southern half of the Great Valley of California. The maximum thickness of the marine Pliocene is at least 4000 to 5000 feet to the south of San Francisco, and 5000 to 6000 feet (*Fernando* formations) in Los Angeles County.

Volcanic ash deposits of later Tertiary age reach a thickness

of several thousand feet in the western Mohave Desert of California (Fig. 206).

Thickness of the Tertiary. — In the above descriptions some details have been given regarding the thickness of Tertiary formations. To summarize for the whole Tertiary, the maximum thickness of the whole system (not including igneous rocks) on the Atlantic Coast is less than 1000 feet, on the western Gulf Coast between 3000 and 4000 feet; in the western interior many thousands of feet, though usually not more than a few thousand feet occur in any one locality, because in no case are all the formations present; and on the Pacific Coast fully 30,000 feet, with a thickness of 10,000 to 20,000 feet shown in many districts. According to these figures it is seen that the thickness of the Tertiary system is comparable to that of ordinary Paleozoic or Mesozoic systems.

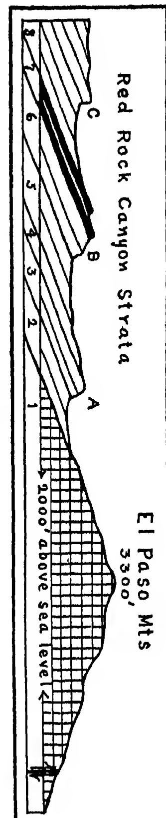


Fig 207

A generalized west-northwest structure section through Red Rock Canyon north of Mojave, California Vertical scale exaggerated Length of section, 3 miles The Red Rock Canyon strata of late Tertiary age are fully 2500 feet thick. They consist mainly of bedded volcanic tuffs, sandy and shaly beds, and some sheets of lava (black bands) They rest unconformably upon the granite of the El Paso Mountains. (After W. J. Miller, "Jour. of Geog.," Vol. 25, 1926, p. 332)

Igneous Rocks. — In the above descriptions, attention has been wholly given to a consideration of the sedimentary rocks (including some tuffs and volcanic ash deposits), but the igneous rocks of Tertiary age are also of very great extent and importance, particularly in the northwestern part of the United States. This igneous activity will be discussed below in connection with the Tertiary physical history of North America.

Physical History

In the interest of more clearly presenting an outline of our unusually detailed knowledge of the complicated physical history

of this comparatively recent (Tertiary) period, we shall depart slightly from our ordinary method by considering first the relations of land and water, basins of deposition and character of sediments in different parts of the continent, etc., after which will follow a

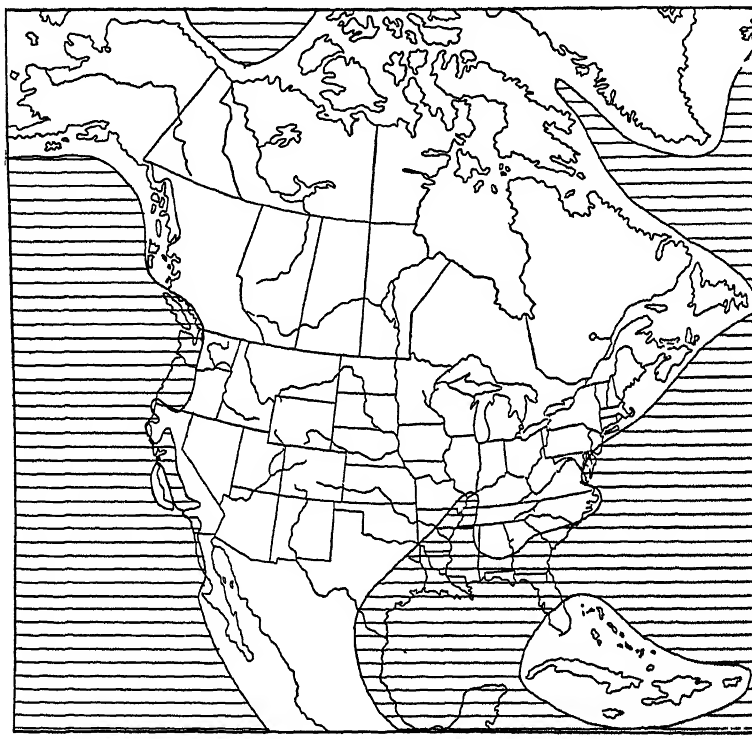


Fig 208

Paleogeographic map of North America during Eocene time. White areas, land, ruled areas, sea The situation was very similar to this in the Oligocene, but with much less water in California. (Principal data, modified by the author, from maps by B Willis and C. Schuchert.)

discussion of the development of relief features in the east and west, and mountain making and igneous activity in the west.

Atlantic Coast. — During most of the time from Eocene to Miocene inclusive, much of the Atlantic Coastal Plain (including

Florida) was occupied by marine water (see Figs. 208, 209). Certain unconformities, especially between the Eocene and Miocene, show that there were some retrogressions and transgressions of the sea. During Eocene time the newly added belt of Cretaceous de-

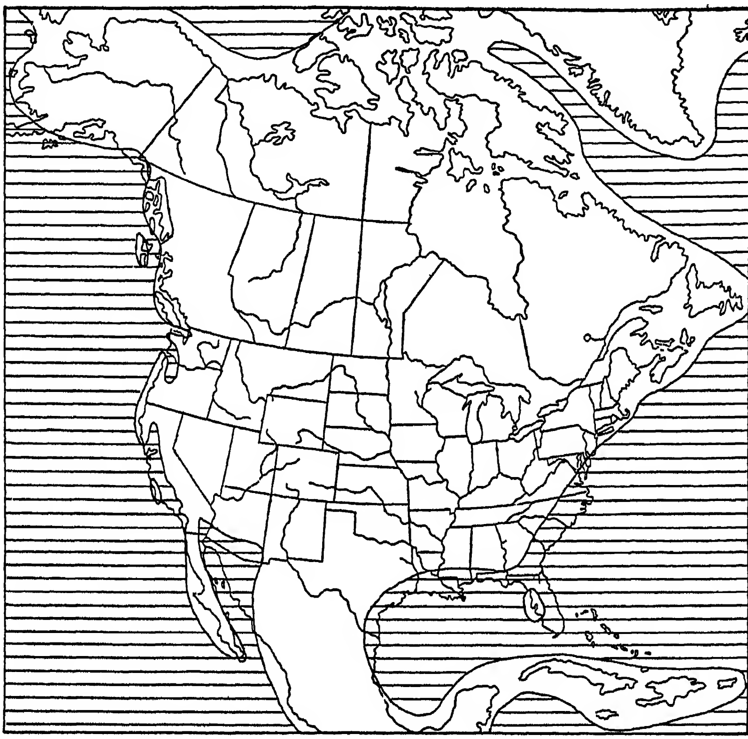


Fig. 209

Paleogeographic map of North America during later Miocene time White areas, land; ruled areas, sea. (Principal data, modified by the author, from a map by B. Willis.)

posits lay along the shore, and the Eocene strata are known to have been mostly derived from the Cretaceous and in part from the more inland older formations. In general, it may be said that, to and including the Miocene, there was a tendency to push the shore line gradually farther eastward by the addition of strips of land.

With the possible exception of the Lafayette, which is usually regarded as of Pliocene age, the only marine strata of Pliocene age comprise the comparatively thin Waccamaw formation on the middle Atlantic Coast.

The Lafayette deposits of North Carolina, according to Stephenson and Johnson, "are present as surficial coverings (10 to 40 miles wide), probably at but few places exceeding 25 to 30 feet in thickness, along the northwestern border of the Coastal Plain province. They occur for the most part at elevations of from 200 to 500 feet and form mouth-like coverings which cap the tops of, and lap down over the slopes of, the pre-Lafayette hills. The materials consist of sandy loams and sands, as a rule coarse and in places arkosic, and having at their base at many places a bed of coarse gravel and cobbles."[1] In Maryland the Lafayette is quite distinctly terrace-like. According to one view it is of continental origin and was deposited as a result of "a comparatively rapid Pliocene uplift in the Appalachian region" (W. H. Dall), which, early in the Pliocene, had become mantled with deep residual soil so that the revived streams picked up and carried great loads of debris which were spread over the relatively flat lands near sea level. Another explanation is that the Lafayette was of marine origin, due to simultaneous depression of the Coastal Plain district and elevation of the Piedmont Plateau and Appalachian areas when "streams gorged with detritus from the decayed, uplifted Piedmont above rushed down to the sea and poured their contents into the ocean" (G. B. Shattuck). The most likely view is that the Lafayette is a normal marine terrace, much like the later ones below described, and that, "with the successive oscillations of the coast line, terraces have been formed at levels where the sea has stood for any considerable period of time" (W. B. Clark). Careful search has failed to produce any marine fossils from the formation.

Gulf Coast. — During Eocene-Oligocene time extensive sedimentation, both marine and non-marine, took place over the Gulf Coastal Plain area. The Mississippian embayment (see Fig. 208) extended northward (to the mouth of the Ohio River) as it did in the Cretaceous, and the unconformity between the Cretaceous and Eocene clearly shows a transgression of the sea over the area in Eocene time. Marine conditions in this embayment were,

[1] The Coastal Plain of North Carolina: North Carolina Geological and Economic Survey, 1912, p. 359.

however, more or less interrupted as proved by the considerable development of non-marine deposits such as lignite beds. Over Florida, the Gulf Coast of Mexico, and much of the coast of Texas, true marine deposition went on during practically all of Eocene and Oligocene times.

During Miocene time the Mississippi embayment was greatly restricted, but marine waters spread over the southern part of the Gulf Coastal Plain from Florida to Mexico, except for a small island in Florida, and over the eastern Coastal Plain of Mexico (see Fig. 209).

The presence of some marine Pliocene strata in Florida and along the Gulf Coastal Plain border shows those areas to have been submerged during portions of Pliocene time at least.

Western Interior-Great Plains. — The extensive folding, faulting, and lava extrusions which marked the close of the Cretaceous period left the western interior topographically rugged with conditions favorable for rapid erosion of the mountains and deposition of sediments in the intermontane basins. As the character of the Tertiary sediments indicates, all sorts of continental deposits were formed, that is in lakes, on river flood-plains, as alluvial fans, as wind-blown deposits, and even as volcanic dust or tuff in many places. Marine deposition was wholly lacking. As shown by the above statements regarding the distribution of the various formations, it is apparent that the principal areas over which sediments were being deposited must have shifted more or less.

That there was very active vulcanism during Tertiary time in this western interior region is proved by the presence of so much volcanic dust and ash. Also in the great area between the Rockies and Sierra-Cascade Ranges, there was tremendous volcanic activity, but this will be described under a separate heading below.

Many of the Tertiary deposits of the western interior now lie at altitudes of from 5000 to 10,000 feet above the sea, and they have been somewhat deformed by tilting or warping.

Pacific Coast. — Summarizing the physical history of the Pacific Coast during Cenozoic time, Ralph Arnold says in part: "Following the period of elevation and erosion at the close of the Cretaceous, the Eocene was inaugurated by a subsidence below sea-level of the greater part of western Washington and Oregon and the western part of central and southern California. Volcanic

activity was pronounced in the early and middle Eocene. Later in the Eocene brackish and freshwater conditions prevailed over the same area. . . . The Oligocene was a period of elevation, with marine conditions restricted to a much smaller area than in the Eocene. . . . The lower Miocene marked a widespread subsidence in the Coastal belt which was followed by a period of mountain

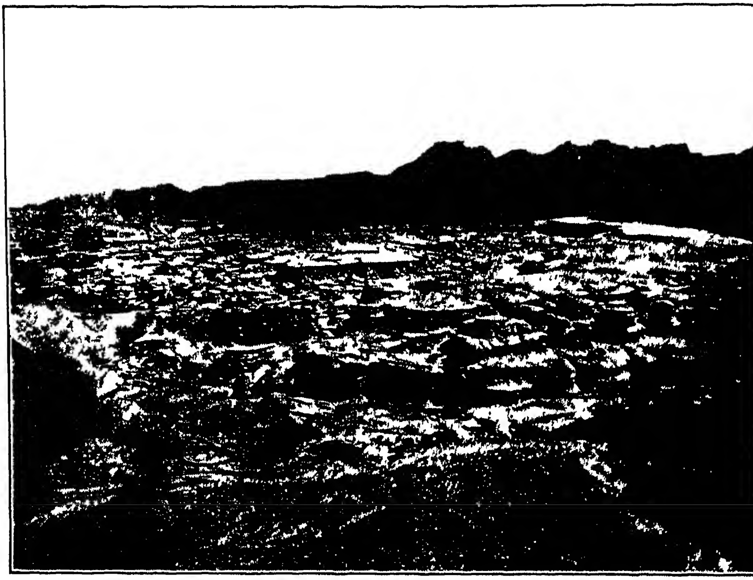


Fig 210

"Toadstool Park". a view in the Bad Lands of western Nebraska The rocks are of Oligocene age. (After Darton, U. S. Geological Survey, *Prof. Paper 17*.)

building (Coast Range region) and great local deformation, vulcanism, etc. . . . The upper Miocene was a period of subsidence, with ideal conditions for maximum deposition of sediments in local basins. During Pliocene and early Pleistocene time there was a continuation of many of the upper Miocene conditions, except that marine environment gave way to freshwater." [1] A period of gen-

[1] Ralph Arnold: *Outlines of Geologic History*, by Willis and Salisbury, p. 248.

eral elevation and great deformation (folding and faulting) took place in the Pliocene and early Quaternary. This included the main development of the Coast Range Mountains, and the uplift of the Sierra Nevada and southern California fault-block mountains.

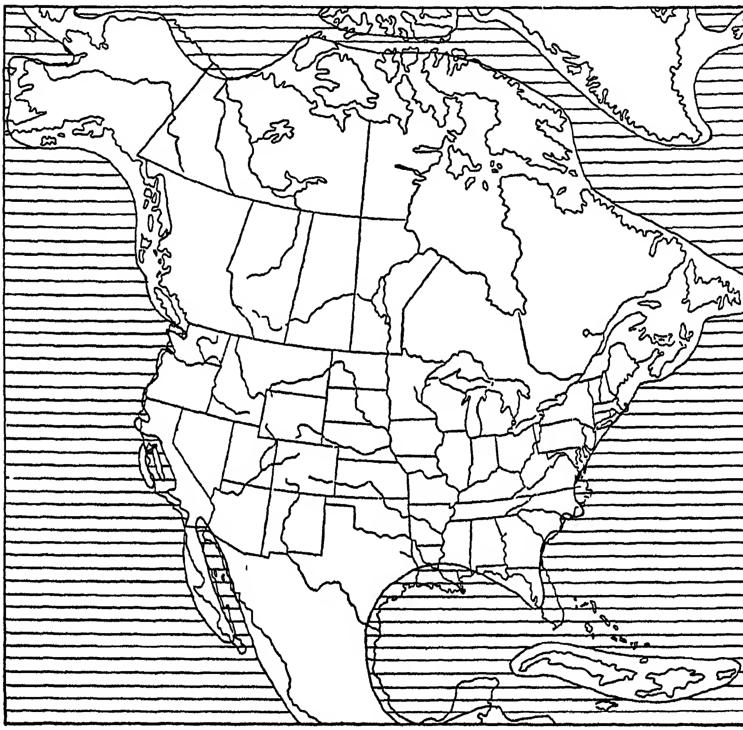


Fig 211

Paleogeographic map of North America during Pliocene time. White areas, land; ruled areas, sea (Principal data, modified by the author, from maps by C. Schuchert and B. L. Clark.)

"In the Coast Range province conditions of sedimentation were subject to great local variation during the Tertiary period. The variations were necessary results of the constantly changing relations of land and sea caused by the many warping movements to which the province was subjected. Tectonic forces were active,

with varying degrees of intensity at different times and in different parts of the Coast Ranges, practically throughout the Tertiary period."[1] Arnold has stated "that within the Tertiary and Quaternary periods, relatively short, geologically speaking, as compared with the earlier divisions of the time scale, probably more distinct and profound movements have taken place on the

Fig 212

Map of the northern Appalachian Range showing the system of parallel ridges and valleys (After U. S. Geological Survey.)

western border of our continent than have occurred over an equal length of time in any of the preceding periods within the limits of North America."[2]

Development of Relief Features in the Eastern United States.—The uplift of the great Cretaceous peneplain was an event of prime importance for the eastern United States, because it literally furnishes us with the beginning of the history of most of the existing relief features of the Appalachian district as well as New York and much of New England. Hence we assert, with

[1] W A English: U. S G S., *Bul.* 768, 1926, p. 15.

[2] Ralph Arnold. *Outlines of Geologic History,* by Willis and Salisbury, p. 228.

emphasis, that all the principal topographic features of this region as we see them today date from the uplift of the Cretaceous peneplain, because they have been produced by the dissection of that upraised surface. This dissection was largely the work of erosion, though more locally (e.g. the eastern Adirondack Mountains) faulting has produced notable effects. All the valleys, great

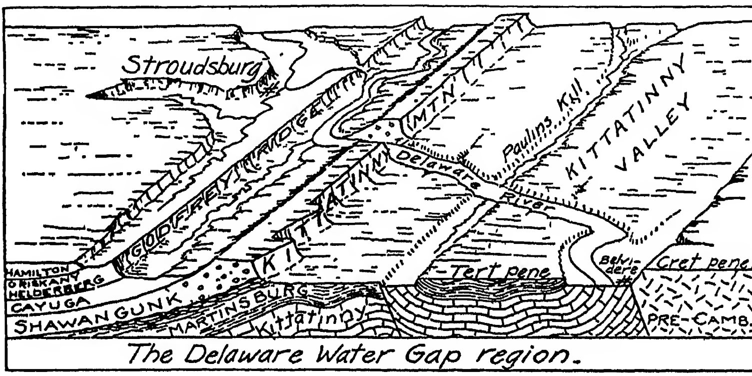


Fig. 213

A block diagram representing the geologic structure, the main ridges and valleys, and the Delaware Water Gap in Pennsylvania-Delaware The Cretaceous and Tertiary peneplain levels are both indicated (Drawn by A. K Lobeck.)

and small, such as the Champlain, Connecticut, Mohawk, Hudson, the Great Lakes valleys, and the valleys of the Appalachians, have been produced since the uplift of the peneplain (Fig. 212).

The uplift greatly revived the activity of the streams, so that they became very active agents of erosion, first cutting channels through the alluvial deposits, and then into the underlying bed rock. Thus these large original streams had their courses determined in the overlying deposits, and when the underlying rocks were reached the same courses had to be pursued entirely without reference to the underlying rock character and structure. Fine examples of such (superimposed) streams, which are now entirely out of harmony with the structure of the regions through which they flow are the Susquehanna, Delaware, and Hudson. Thus the Susquehanna cuts across a whole succession of Appalachian ridges,

while, in accordance with the same explanation, the Delaware cuts through the Kittatinny ridge at the famous Delaware Water Gap (Fig. 213). The lower Hudson pursues a course no less out of harmony with the country through which it passes. It flows at a considerable angle across the old Taconic folds above the Highlands, after which it passes through a deep gorge which it has cut through the hard granites and other rocks of the Highlands. The simple explanation is that the Hudson had its course determined upon the surface of the upraised Cretaceous peneplain, and that it has been able to keep that course in spite of the discordant structures of the underlying rocks. The seemingly anomalous courses of the Delaware, Potomac, Susquehanna, etc., are to be similarly explained.

But while the great master streams were thus cutting deep trenches in hard and soft rock alike, numerous side streams or tributaries came into existence and naturally developed along the belts of weak rock and in harmony with the geologic structures. This principle is especially well illustrated by all of the streams now occupying the valleys between the Appalachian ridges (Fig. 212).

After the uplift of the peneplain, the larger streams cut down their channels most rapidly and were the first to reach "grade," that is a condition in which, because of low velocity, they could no longer cut down their channels, though the widening process could continue because of side cutting due to meandering of the streams back and forth from one side to the other of the channels. The commonly occurring, deep, broad-bottomed, stream-cut valleys, in the area under discussion, show that many of the streams had reached graded, or nearly graded, condition even by the close of the Tertiary (Fig. 213). In the northern Appalachian district, at least, we have evidence to show that after the streams had reached grade there was an appreciable renewed uplift of the land which again revived the activity of the streams. Thus the broad Hudson Valley, with minor hills rising above its surface, was produced when the Hudson was well along toward a graded condition and then, as a result of this late Tertiary uplift of the land, the present narrow and fairly deep inner channel of the Hudson was formed. The Hudson did not reach grade in this inner channel, its work having been interrupted by both the subsidence of the land and the spreading of the great ice sheet over the region.

This inner channel of the Hudson has been traced for fully 100 miles eastward beyond the mouth of the present river. The Coast and Geodetic Survey has made a detailed map of the ocean bottom near New York City, and the submerged channel of the Hudson River is clearly shown as a distinct trench cut into the continental shelf. Even in the Hudson Valley above New York City, the narrow inner rock channel has a depth of hundreds of feet and is mostly submerged below tide water. Without question, this submerged Hudson channel was cut when the region was dry land, and thus we have positive proof that, late in the Tertiary and possibly extending into the early Quaternary, the region of southeastern New York was notably higher than it is today. Conservative estimates place the amount of elevation greater then than now at not less than 2000 feet because the end of the Hudson channel is submerged to that extent.[1] The coast was then at what is now the edge of the continental shelf or platform about 100 miles east of the present coast line. That this greater altitude was before the Ice age is proved by the fact that the inner Hudson channel now contains much glacial debris filling.

By similar reasoning, based upon the drowned valleys of the Maine coast and the lower St. Lawrence, we know that all of the middle Atlantic seaboard region, at least, was notably higher in late Tertiary time than now.

The Mississippi Valley area also appears to have been notably elevated during late Tertiary time, and hence the major (erosion) relief features of that great area, as we now know them, have been produced by the dissection of that upraised area by streams.

Mountain Making and Development of Relief in the West.[2] — In North America, as well as other continents, the Tertiary was a period of unusual mountain-making activity. Many of the present great mountain ranges of the earth actually had their birth and principal development during this period, while others were

[1] It has been suggested by Chamberlin and Salisbury (*Geology*, Vol. 1, p. 529) that the very end of the Hudson, and other submerged channels, may have been deepened by tidal scouring and, if so, the figure (2000 feet) generally given may be too high. At any rate the Hudson channel at the Highlands is submerged nearly 800 feet, which certainly implies an altitude of more than 1000 feet greater than now when the river was there actively eroding.

[2] The topographic influence of Tertiary vulcanism in the West will be described under another heading.

rejuvenated and brought essentially to their present form and altitudes.

Coast Ranges. — This belt was somewhat affected by deformative movements toward the close of the Jurassic, as we have already seen, but probably not more than a chain of islands was then developed. Another time of moderate elevation occurred during the Eocene. The Oligocene was a time of considerable elevation and erosion in the Coast Range district, though the relief was only moderately strong, as shown by the character of the sediment which was deposited during the Oligocene in the limited areas of southern California and western Oregon and Washington

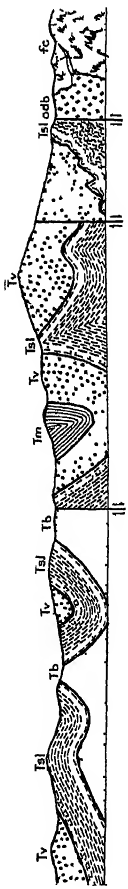


Fig 214

Structure section across a portion of the Coast Range Mountains of central-western California, showing the character of the Tertiary folding and faulting. Length of section, 9 miles. *fc*, Jurassic? rocks, *odb*, pre-Tertiary intrusive rock; *Tb*, *Tsl*, Oligocene sandstone and shale, *Tv*, *Tm*, Miocene sandstone and shale. The profound fault at the right is the one along which renewed displacement occurred to cause the San Francisco earthquake of 1906. (After Branner, Newsom and Arnold, U. S. Geological Survey, Folio 163.)

In middle Miocene time there was important diastrophic activity throughout the Coast Range region, but especially in middle-western California. The movements involved folding, faulting, and elevation which were locally intense.

Most profound of all Tertiary diastrophic activity, however, was the real "Coast Range Revolution" which marked the close of the Pliocene and the early Quaternary on the Pacific Coast. The Coast Range Mountains were then mainly produced by uplift accompanied by much folding and faulting. Strata of Tertiary age and older, many thousands of feet thick, were involved in this intense orogenic activity.

The uplift of the fault-block mountains of southern California also began at the close of the Pliocene.

Other important mountain-making movements took place

during the Quaternary, with minor activity continuing to the present time. The combination of the various diastrophic movements and erosion in the Coast Range belt since early Tertiary time has given rise to the Pacific border mountains as we see them today.

Sierra Nevada and Cascade Ranges. — As already stated the Sierra Nevada Mountains were produced by crustal disturbance toward the close of the Jurassic period. From that time till late in the Miocene epoch the mountain mass had undergone profound

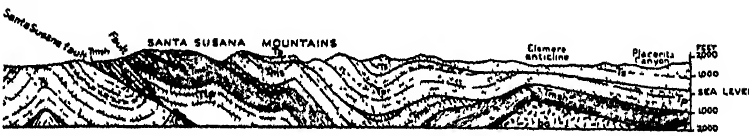


Fig 215

A nearly north-south structure section through a part of western Los Angeles County, California, proving that the region was strongly folded and faulted after late Pliocene (Saugus) strata were deposited. Length of section, 6.5 miles. Symbols: *bc* = pre-Cretaceous crystalline rocks; *Ttp* = Miocene (Topanga) sandstone; *Tmsh*, *Tms* = Miocene (Modelo) shale and sandstone; *Tp* = early Pliocene (Pico) sandstone; and *Ts* = late Pliocene (Saugus) sandstone. (After W. S. Kew, U. S. Geological Survey, *Bul.* 753.)

erosion, so that it was reduced to a range of hills or low mountains with no great relief features. In other words, it approached the condition of a peneplain. Then, late in the Miocene or early in the Pliocene, there began a tremendous rejuvenation of the range, caused by the development of profound faulting along the eastern side. The vast earth-block was tilted westward with steep eastern front and long gradual slope toward the west, with the crest of the block forming the summit of the range (Fig. 218). The maximum amount of displacement along this fault zone is no less than 15,000 feet and, in spite of subsequent erosion, the fault-scarp still stands out as a topographic feature usually several thousand feet high. That the faulting has not yet ceased is evidenced by the Inyo earthquake of 1872, when a renewed displacement of 10 to 25 feet took place along the fault zone for many miles. The mighty canyons (e.g. Yosemite) and other relief features of the Sierra Nevada Mountains as we know them today have been sculptured out of the great tilted earth-block by weathering and erosion.

Fig 216

A small anticline in Upper Miocene sandstone and shale on Avenue 64, Los Angeles, California. (Photo by the author.)

Fig. 217

A large anticline in Upper Miocene strata near Simmler, San Luis Obispo County, California. (Photo by Wayne Loel.)

The Cascade Mountains, too, appear to have approached the peneplain condition by late Tertiary time, when a vigorous rejuvenation took place by an arching or bowing of the surface rather than by profound faulting. The old surface, uplifted thousands of feet, has been deeply dissected by erosion. Great volcanic cones, such as Mt. Rainier and Mt. Hood, rise above the general level of the platform.

Great Basin and Colorado Plateau.— About the same time (later Tertiary) the whole Great Basin region between the Sierra Nevada and the Wasatch Mountains of Utah was also notably affected by faulting. The steep western front of the Wasatch represents a profound fault, while many of the north-south Basin Ranges of Nevada are tilted earth-blocks (Fig. 218). Great thrust faults of Tertiary age, involving miles of displacement, have been found recently in southern Nevada.

The Cenozoic history of the Colorado Plateau region still presents important problems for future studies. According to Dutton the Plateau was raised, more or less periodically, fully 20,000 feet during Tertiary time, but its surface now shows an altitude of only 7000 to 8000 feet, because of deep erosion during its uplift. As a result of the rejuvenation of this region, the Colorado River was very actively revived and has carved out the Grand Canyon since the early Tertiary. Later investigations, however, seem to show that the rejuvenation was much later, probably late Pliocene, and that most, if not all of the Grand Canyon, is of post-Tertiary age.

Rocky Mountain and Western Interior Regions. — Late in the Tertiary much of the

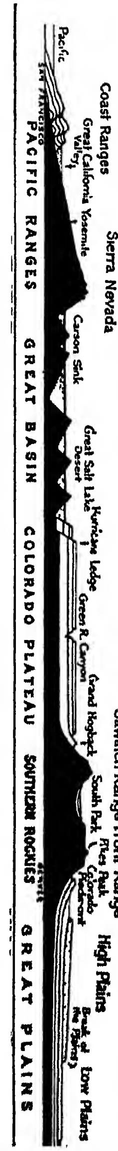


Fig. 218

A diagrammatic structure section across the western United States. The relations of various physiographic provinces are clearly shown. (Drawn by A. K. Lobeck.)

Rocky Mountain region was also greatly rejuvenated by an uplift or upwarp, unaccompanied by folding of the strata. That this

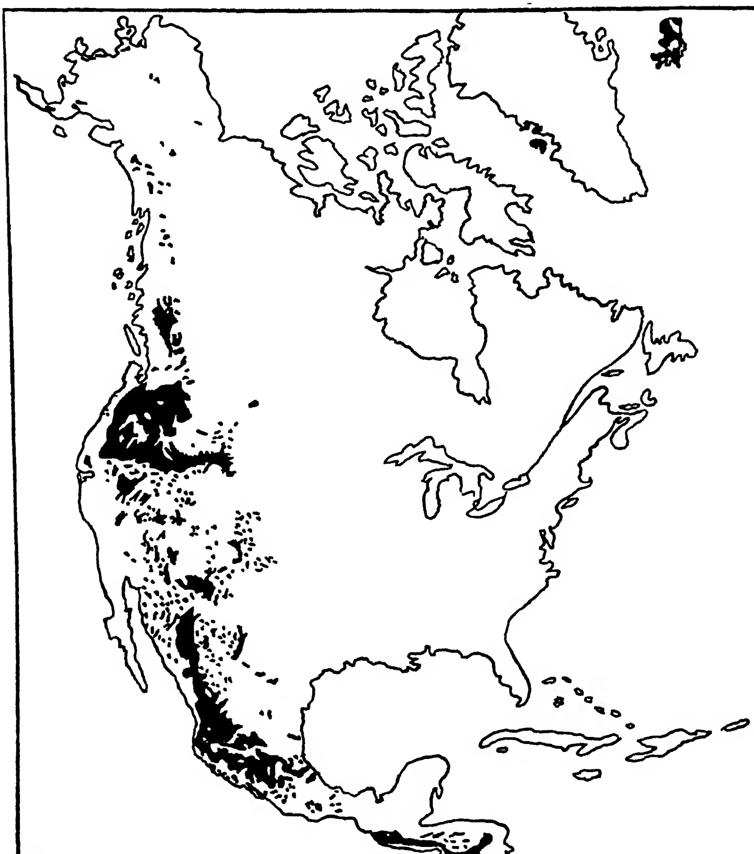


Fig 219

Map showing the surface distribution (areas of outcrops) of Tertiary and later volcanic rocks in North America. (Modified by W. J M after Willis, U S Geological Survey)

upwarp amounted to some thousands of feet is distinctly proved by the fact that the Miocene beds east of the Rockies are so tilted that they are 3000 feet higher close to the mountains than they

are farther east. Also the fact that many large areas of Tertiary deposits now lie from 5000 to even 10,000 feet above sea-level, rather clearly indicates notable elevation since their deposition, because such deposits must have been formed in intermontane basins much nearer sea-level, like the recent deposits of the Great Valley of California.

The dissection by erosion of the usually comparatively soft and only moderately tilted deposits of Tertiary age in the western interior has given rise to much of the "Bad Lands" country, so called because of the difficulty early explorers had in travelling across that rugged region (Fig. 210).

Igneous Activity. — There was tremendous volcanic activity in the Cordilleran region of western North America during Tertiary time. Most of this vulcanism occurred during the later Tertiary, and gradually diminished during the Quaternary (see map Fig. 219). The building up of the vast lava region, known as the Columbian Plateau, covering over 200,000 square miles between western Wyoming (including Yellowstone Park) and the Cascade Mountains of Washington, Oregon, and northern California took place at this time. Norton has clearly and concisely stated the principal facts as follows: "For thousands of square miles the surface is a lava plain which meets the boundary mountains as a lake or sea meets a rugged and deeply indented coast. . . . The rivers which drain the plateau — the Snake, the Columbia, and their tributaries — have deeply trenched

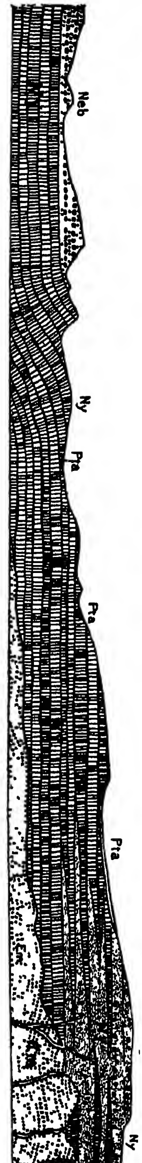


Fig. 220

Structure section in central Washington showing sheets of Miocene lava piled up to a thickness of fully a mile. Length of section 11 miles *Em*, Eocene sandstone; *Ny*, Miocene lava (basalt); *Neb*, Miocene strata; *Pta*, Pleistocene lava Note the distinct fold in the lava (After G. O Smith and Calkins, U. S. Geological Survey, Folio 86.)

it, yet their canyons, which reach the depth of several thousand feet, have not been worn to the base of the lava except near the margin and where they cut the summits of mountains drowned beneath the flood. Here and there the plateau has been deformed. . . . The plateau has been built like that of Iceland, of innumerable overlapping sheets of lava (Fig. 220). . . . The average thickness of flows seems to be about seventy-five feet.

Fig 221

Lassen Peak in northern California in eruption August 22, 1914. Smoke and volcanic ash rose to a height of 10,000 feet (From a photograph by R E Stinson, Red Bluff, Calif)

"The plateau was long in building. Between the layers are found in places old soil beds and forest grounds and the sediments of lakes. . . . So ancient are the latest floods in the Columbia Basin that they have weathered to a residual yellow clay from thirty to sixty feet in depth and marvelously rich in the mineral substances on which plants feed. In the Snake River Valley the latest lavas are much younger. Their surfaces are so fresh and undecayed that here the effusive eruptions may have continued to within the period of human history." [1]

Volcanic activity must have been very pronounced along the Rockies during the Tertiary, as shown by extensive and often very thick deposits of tuff or volcanic ash (e.g. San Juan and Florissant formations). Many volcanoes also broke forth on the Colorado Plateau of Utah, New Mexico, and Arizona, in the latter state especially there being cones exhibiting all stages of denudation from very recent cinder cones to others where only the merest remnants or "volcanic necks" are left.

Tertiary vulcanism in Mexico was very vigorous and ex-

[1] W. H. Norton: *Elements of Geology*, pp. 400–401

tensive, in fact comparable with that of the western United States.

In the northern Coast Range mountains of the United States there was considerable volcanic activity in the Eocene and much throughout the Range in the Miocene as proved by the numerous sheets of lava, dikes, and beds of tuff associated with the Miocene strata.

Very pronounced vulcanism occurred in the Cascade Mountain region during the Eocene and to the middle Miocene. During

Fig. 222

A sheet of columnar lava lying between beds of volcanic dust, near Crater Lake, Oregon. (Photo by the author.)

Pliocene time there was great volcanic activity with outpourings of lava in the Sierra Nevada and Cascade Mountains. At that time the Miocene gold-bearing stream gravels of California were buried under the lava. Many well-known volcanic mountains, such as Shasta, Hood, Rainier, etc., date from that time. In fact this period of vulcanism has not altogether ceased at the present day, as shown by a renewal of activity of Lassen Peak (altitude 10,437 feet) in northern California on May 30, 1914. During a period of several years from 1914 there were hundreds of erup-

tions of the mountain, in all cases fragmental materials only having been ejected sometimes to a height of 5000 to 10,000 feet above the mountain (Fig. 221). The peak has become almost inactive again. The eruptions of cinders and lava at Cinder Cone, only 10 miles from Lassen Peak, occurred not over 200 years ago. Other quite recent cinder cones are known in southern California and Arizona.

Foreign Tertiary

Eocene. — Just after the emergence of much of Europe at the close of the Mesozoic, there were certain basins of deposition such as lakes, estuaries, etc. Early in the Eocene, however, a great submergence set in, allowing marine waters to spread over a considerable part of western and much of southern Europe. The southeastern British Isles, the northern border of France, Belgium, Holland, the northern border of Germany, the site of the Pyrenees, Italy, all but the axis of the Alps, much of southeastern Europe, and northern Africa were submerged (see Fig. 223). This greatly expanded mediterranean of Europe also extended eastward across southwestern Asia, except southern Arabia and southern India, to connect with the Indian Ocean through the Bay of Bengal. A narrow sound along the eastern side of the Urals connected this mediterranean with the Arctic. In this vastly expanded interior sea true marine deposition took place, the most characteristic formation being known as Nummulitic limestone, so called because it is made up chiefly of shells of a certain genus (Nummulites) of unusually large Foraminifers. Perhaps no other formation in the crust of the earth, built up essentially of the remains of but one genus of organism, is so widespread and thick, its thickness at times reaching several thousand feet. This marine Nummulitic limestone now occurs at altitudes of 10,000 feet in the Alps, and fully 20,000 feet in Thibet. Limestone of this age was quarried for the building of the Egyptian pyramids.

During Eocene time also the island region along the eastern coast of Asia was largely submerged as well as the eastern coasts of Australia and South America (in Argentina and Brazil). Land seems to have been continuous in the northern hemisphere except for the narrow strait or sound just east of the Ural Mountains.

Toward the close of the Eocene the Pyrenees Mountains were upraised by folding, while initial (though moderate) orogenic

movements took place in the regions of the Apennines, Alps, and probably Himalayas as well as some other mountain districts.

Oligocene. — The Oligocene is best known in Europe, while in many other parts of the world it has not yet been separated from the Eocene or Miocene. During the Oligocene a shallow sea transgressed over northern Germany. In many places there were lagoons, estuaries, and even basins in which terrestrial deposits were formed. Some beds of gypsum, salt, and brown coal (lignite) were formed. Oligocene strata are especially well developed

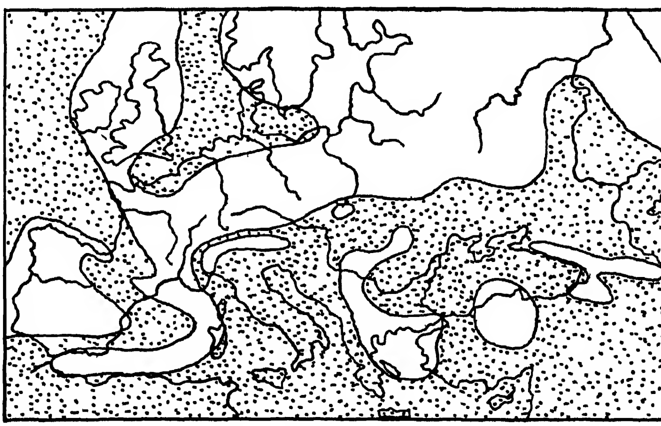


Fig. 223

Sketch map showing the relations of land and water in Europe during middle Eocene time. Dotted areas show water (After Kayser.)

throughout southern Europe. In Italy, marine deposits of this age have an estimated thickness of 12,000 feet. In southern Europe true marine conditions prevailed, though continental deposition also occurred.

There was much igneous activity during this epoch, particularly in Bohemia, Ireland, Scotland, Iceland, and in the vicinity of Vienna.

More or less severe orogenic movements affected certain districts such as the Balkan and Carpathian Mountains toward the close of the epoch.

Oligocene rocks are also quite certainly present in the Cau-

casus Mountains, southwestern Asia, and northern Africa, but they have not been much studied in other countries.

Miocene. — Viewed in a broad way, the Miocene land and water areas of Europe were much as they had been in the Eocene, all but the northern coast of Germany again becoming dry land. Marine waters occupied parts of the Atlantic borders of France and the Iberian peninsula, while southern Europe was largely submerged as in the Eocene, except for considerable land masses occupying such areas as the interior of Spain and France, portions

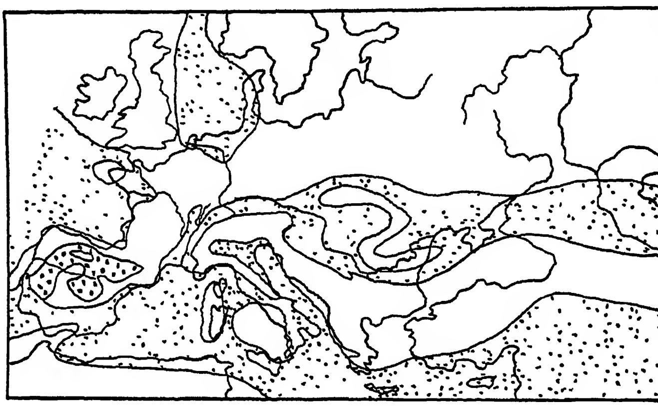


Fig 224

Sketch map showing the relations of land and water in Europe during middle Miocene time Area of coarse dots, continental deposition; areas of small dots, marine waters (After Kayser.)

of the sites of the Alps, Pyrenees, Carpathians, Apennines, etc., which had been more or less affected by orogenic movements before the Miocene (see map Fig. 224). A remarkable formation, worthy of special mention, is an extensive conglomerate several thousand feet thick along the northern side of the present Alps. This conglomerate has considerably controlled the topography, for instance in the vicinity of Lucerne.

The vast Eocene mediterranean across southwestern Asia was not continued into the Miocene. Eocene strata, both marine and non-marine, occur in northern Africa and Syria, but not in the Persian region. Though not yet well studied, Miocene strata are

well developed in southern Asia, Japan, and northeastern Asia and Australia. In South America the Miocene is extensively shown in Argentina and probably also on the western coast of the continent.

Important mountain building occurred in Europe and Asia in the middle and late Miocene. Though initial movements had affected the sites of the Alps, Apennines, and probably the Himalayas, these mountains were greatly elevated by tremendous

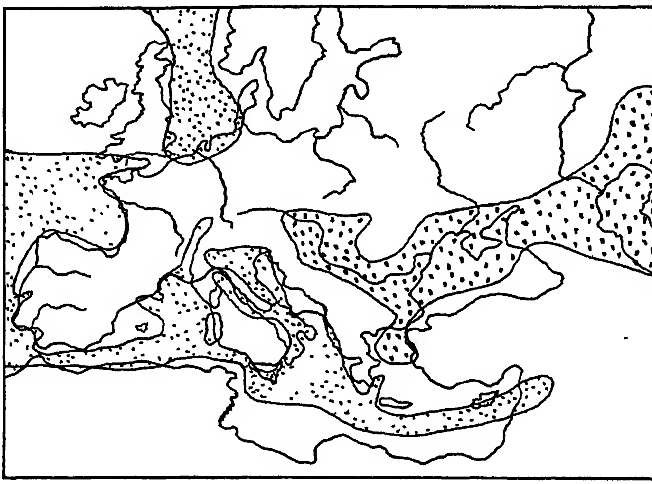


Fig. 225

Sketch map showing the relations of land and water in Europe during middle Pliocene time. Small dots, marine waters, coarse dots, areas of continental deposition. (After Kayser)

orogenic movements in the Miocene.[1] The Caucasus Mountains were also upraised not earlier than in late Miocene, since Miocene strata are there found about 7000 feet above sea-level.

Considerable igneous activity accompanied the late Miocene orogenic movements.

Pliocene. — The Pliocene opened with comparatively little of Europe under marine waters, only a little of southern England,

[1] There appears to be some doubt as to whether the principal orogenic movement in the Himalayas occurred at the close of the Eocene or in the Miocene.

Belgium, the northwestern border of Germany, a little of southern France, and much of Italy having been submerged (see map Fig. 225). Only in Italy are thick marine deposits known where the sediments washed from the newly built Apennines accumulated to a thickness of from 1000 to 3000 feet. Since some of these deposits now lie at altitudes of 2000 to 3000 feet, it is evident that the Apennines were again notably upraised after the deposition of the Pliocene sediments. Volcanoes were active in the Mediterranean region, especially in Italy and Sicily, where volcanoes like Vesuvius and Etna began their eruptions.

In southeastern Europe conditions were favorable for much deposition of continental material — lake, river, and terrestrial deposits.

Marine Pliocene extends up the Nile Valley for many miles. As a result of the erosion of the newly upraised Himalayas, a deposit of sandstones, conglomerates, clays, etc , several thousand feet thick, accumulated at the southern base of those mountains during Pliocene time.

In South America Pliocene deposition took place over much of southern Argentina, deposits of this age being upturned on the eastern flank of the southern Andes.

Climate

During earlier Eocene time the climate of North America was in general notably cooler and drier than that of the present day. This was due mainly to the influence of the great newly formed Rocky Mountains. Glacial deposits of early Eocene age have been found in Colorado.

From middle Eocene to middle Miocene time North America had in general a warm-temperate, moist climate because the high mountains of the west were in such a worn down condition that the warm moisture-laden winds from the Pacific were free to sweep across the relatively low lands.

During the later Eocene the existence of a subtropical climate well toward the northern boundary of the United States, and in Europe as far north as Germany and the British Isles, is abundantly proved by the character of the fossil plants and animals.

Over the Great Plains region of the United States the climate, now semiarid, was distinctly moister in the later Eocene and earlier

Miocene, as indicated by the great deposits of lignite which prove the existence of prolific plant life in swamps. Fossil Figs, Palms, and Magnolias in the western interior indicate much warmer and moister climate than now.

Oligocene climate appears to have been somewhat cooler (perhaps warm-temperate) in western North America, and tropical in southeastern North America. In Europe the warm climate of the Eocene seems to have continued, for Palms lived in northern Germany.

Viewed in a broad way, the climate of the continent gradually became cooler and drier from the middle Miocene to the late Pliocene, inclusive, in places reaching Arctic conditions. This was caused by widespread uplifts of the land over the continent, but more especially in the Cordilleran region.

During much of Miocene time the climate of the Pacific Coast was almost like that of today. On the Atlantic Coast a comparatively cool current, apparently from the north, drove out the warm water forms of the earlier Tertiary. In the western interior region of the United States, subtropical plants gave way to temperate climate plants. In Europe the warm climate of the later Eocene continued into the earlier Miocene and became distinctly cooler (temperate) in the later Miocene.

The Pliocene was in general cooler than the Miocene, in fact, gradually increasing from temperate to sub-Arctic conditions in the waters along the California coast, and even to Arctic conditions in the British Isles region. Thus, passing upward in the British Pliocene series, the number of Arctic fossil forms increases from a few per cent to 50 or 60 per cent. An exception to the above general conditions appears to have been along the Atlantic Coast of the United States, where the marine water was rather warmer than it had been during the Miocene. As judged by the plants, the lands apparently had not become so correspondingly cold during the Pliocene.

The grand climax of Cenozoic cold was reached in the succeeding Glacial epoch of the Quaternary period.

Economic Products

A very large production of petroleum in the United States comes from southern California, where it is obtained mostly from

Tertiary shales and sandstones. It seems probable that this petroleum originated from the decomposition of countless numbers of Diatoms in certain of the shales.

Lignite (or brown coal) underlies thousands of square miles of both the Gulf States and the western interior regions, as well as smaller areas on the Pacific Coast. There are also important lignite deposits in Europe, particularly in Germany.

Many important gold deposits of California occur in Tertiary river gravels, which are often capped by lava. The famous gold deposits of Cripple Creek, Colorado, and Tonopah, Nevada, and the copper deposits of Butte, Montana, all occur as veins in, or adjacent to, Tertiary igneous rocks.

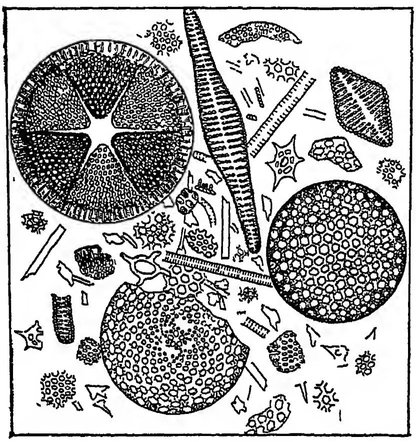


Fig. 226

Diatoms from diatomaceous shale of Miocene age at Lompoc, California. Very much enlarged (After California State Mining Bureau)

Valuable phosphate deposits occur in the Tertiary limestones of Florida.

Life of the Tertiary

Taken as a whole, the life of the Cenozoic era was markedly different from that of the Mesozoic. Even in the Tertiary period the most important groups of plants and animals had a decidedly modern aspect. Most of the plants and the invertebrate animals of the Tertiary period belonged to genera which still exist, while the present-day species gradually increased from a small percentage in the Eocene to a large percentage in the Pliocene. Among the Vertebrates, the Fishes, Amphibians, Reptiles, and Birds differed but little from those of today. The Mammals, however, which were small, primitive, and relatively rare throughout the Mesozoic, showed a wonderful development both in number of individuals and diversity of forms. The Mammals are, therefore, the most interesting and characteristic organisms of Tertiary time.

Plants

Vegetation had assumed a rather distinctly modern aspect well before the opening of the Cenozoic era, the great revolution from ancient to modern types having taken place about the middle of the Mesozoic era. During the Tertiary, however, there was notable progress toward even more modern conditions, so that

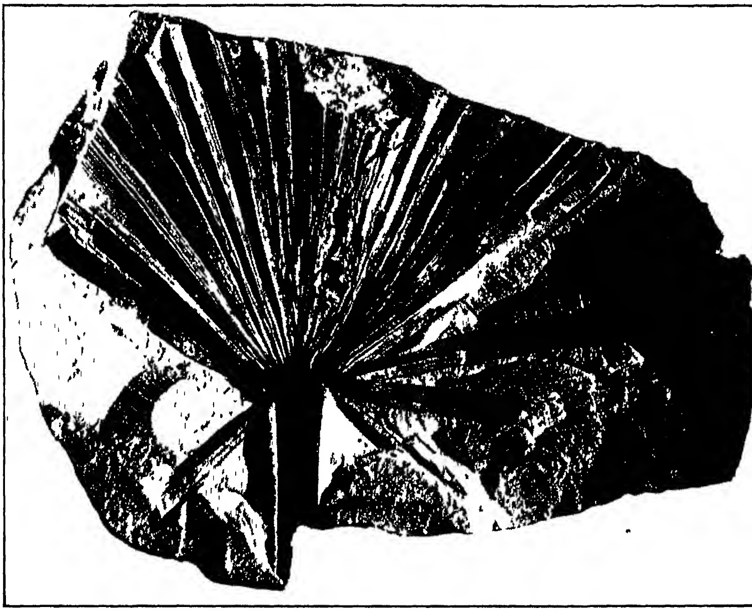


Fig 227

A well-preserved fossil Palm, *Thrinax eocenica*, from the Eocene of Georgia. (After Berry, U S. Geological Survey, Prof Paper 84.)

many genera became the same as now and gradually more and more present-day species were introduced.

Among the simplest or single-celled plants, the *Diatoms* deserve special mention. In certain times and places they swarmed in the Tertiary waters. "The microscopic plants which form siliceous shells, called Diatoms, make extensive deposits in some places (Fig. 226). One stratum near Richmond, Virginia, is 30 feet thick

and is many miles in extent; another, near Monterey, California, is 50 feet thick, and the material is as white and fine as chalk, which it resembles in appearance; another, near Bilin in Bohemia, is 14 feet thick. . . . Ehrenberg has calculated that a cubic inch of the fine earthy rock contains about forty-one thousand millions of organisms. Such accumulations of Diatoms are made both in fresh waters and salt, and in those of the ocean at all depths."[1]

During the earlier Tertiary, as we have learned, the climate of Europe and the northern United States was warm temperate to even subtropical and there flourished such trees as *Palms* (Fig. 227), *Laurels*, *Oaks*, *Willows*, *Chestnuts*, etc., with the addition of *Magnolias*, *Figs*, *Poplars*, *Ferns*, etc., in the western interior of the United States and southern Canada. As far north as Greenland and Spitzbergen, there were forests with *Maples*, *Camphor trees*, *Figs*, *Laurels*, *Cypresses*, *Poplars*, and *Sequoias*. The Sequoias, which are of special interest, began in the late Jurassic; attained their culmination in numbers and species in the Tertiary; and are now represented by only two species, — the so-called Big Trees and the Redwoods, — which are wholly confined to California. During the Tertiary they ranged from Greenland on the north to New Zealand on the south, often in great forests.

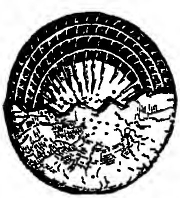


Fig 228

An Eocene Foraminifer, *Nummulina levigata*. (From LeConte's "Geology," courtesy of D. Appleton and Company)

In the later Tertiary the distinctly cooler climate in the higher latitudes caused a disappearance of the warm climate plants such as the Palms from Europe, and the Palms, Figs, Magnolias, etc., from the western interior of North America.

So far as known, the *Cereals* had not yet appeared in the Tertiary, but the *Grasses* became abundant and must have had an important influence in the development of the principal groups of herbivorous Mammals.

Animals

Since the Tertiary invertebrates were in nearly every way so similar to those of today, we shall give special attention to only a few features of interest.

Among **Protozoans,** the *Foraminifers* were exceedingly abundant and often remarkable for their great size. Of these the

[1] J. D. Dana: *Text-book of Geology*, 5th ed., pp. 391–393.

Nummulites, so called because coin-shaped, have already been referred to as making up great limestone deposits in the Old World Eocene. They attained a diameter as great as half an inch to an inch (Fig. 228).

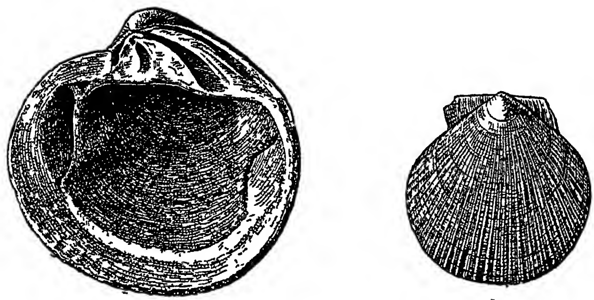
Fig. 229

Large Oyster shells, *Ostrea georgiana*, in Eocene strata of Georgia. (After L. W Stephenson, Geol. Sur. Ga., Bul 26)

Porifers, Cœlenterates, Echinoderms, and Molluscoids were almost wholly modern in character, with Crinoids and Brachiopods both rare.

Among **Mollusks** both *Pelecypods* (Figs. 229, 230) and *Gastropods* (Fig. 231) were exceedingly common, perhaps more so than ever before, and of very modern aspect. *Oysters* appear to have reached their culmination in size at least, some having grown to a length of ten to twenty inches and a width of six or eight inches (Fig. 229). *Cephalopods*, as we have learned, diminished remarkably at the close of the Cretaceous, the great groups of the *Am-*

monites and *Belemnites* having disappeared, while the *Nautiloids* (e.g. Nautilus) were more diversified and widespread than now. The *Dibranchs* were of the modern Squid and Cuttlefish types.

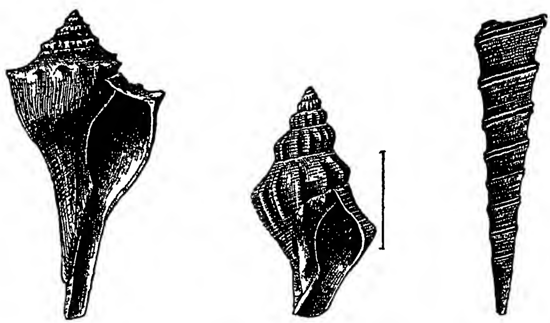


a *b*

Fig 230

Tertiary Pelecypods. *a Venericardia marylandica* (Clark and Martin); *b, Pecten choctanensis* (Aldrich) (After Maryland Geological Survey)

Among **Arthropods** all the principal groups except the simplest (e.g. Trilobites and Eurypterids) were represented, the *Crabs*



a *b* *c*

Fig 231

Tertiary Gastropods: *a, Fulgur carica; b, Strepsidura subcalarina; c, Turritella potomacensis.* (All from Maryland Geological Survey)

among the *Crustaceans* having become numerous and varied. *Insects* are known in far greater numbers and variety than from

any preceding period. All the important groups or orders were represented, including the highest, such as Moths, Butterflies, Beetles, Bees, and Ants. The prolific vegetation of the period was of course very favorable for Insect development.

In a single Miocene stratum a few feet thick at Oeningen, near the Swiss border, more than 900 species of Insects have been found. "In some places the stratum is black with the remains of Insects. The same stratum is also full of leaves of Dicotyls, of which Heer has described 500 species. Mammalian remains and also Fishes

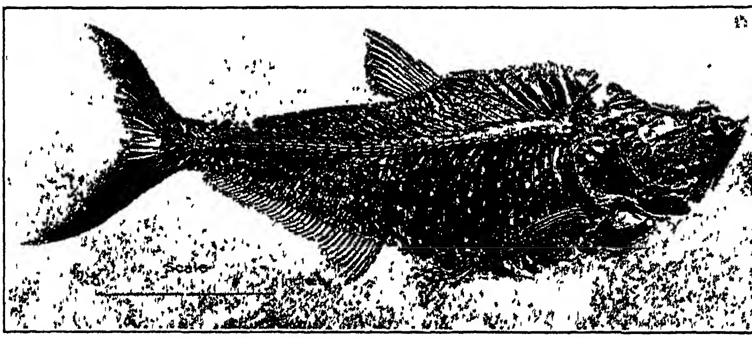


Fig 232

A nearly perfect fossil Teleost Fish, *Diplomystus densatus*, from the Eocene of Wyoming (After Veatch, U. S Geological Survey, Prof Paper 56.)

are found. . . . Doubtless, at Oeningen, in Miocene times, there was an extensive lake surrounded by dense forests, through which ran a small river emptying into the lake; and the Insects drowned in its waters, and the leaves strewn by the winds on its surface, were cast ashore by the waves. . . . Over 500 of the Oeningen Insects were Beetles."[1]

Another remarkable occurrence of fossil Insects is in the amber of northern Germany, especially on the shores of the Baltic Sea, where fully 2000 species have been obtained. The amber is a fossil resin of early Oligocene age derived from certain Conifers. The Insects were caught in the resin while it was still soft and sticky and they were thus literally embalmed and perfectly preserved to the present day in the often quite transparent amber.

[1] J. Le Conte: *Elements of Geology*, 5th ed., p. 534.

At Florissant, Colorado, certain fresh water shales of Oligocene (?) age are said to be black with the remains of Insects. Over 2000 species are represented as well as various plants, Fishes, and even a Bird with well-preserved feathers.

Fishes. — These were in general much like those of the later Mesozoic, though even more modern in aspect. *Teleosts* (Fig. 232) predominated, but *Sharks* were abundant and of great size — 60 to 80 feet long — with fossil teeth up to 5 or 6 inches long occurring in immense numbers in some places as, for example, the Atlantic Coast of the United States (Fig. 233).

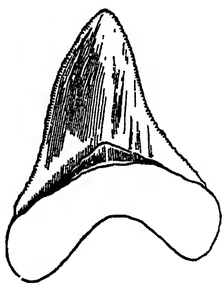


Fig. 233
A Shark's tooth from the Eocene of the Gulf Coastal Plain Length of tooth, 6 in. (After Gibbes.)

Amphibians. — After their great development in the late Paleozoic, the Amphibians never again assumed much importance. In the Tertiary they were represented only by such modern types as Salamanders, Frogs, and Toads.

Reptiles. — These, too, were quite modern in character, with Lizards, Snakes (all non-poisonous), Crocodiles, and Turtles all common and varied.

Birds. — These were much more advanced and numerous than in later Mesozoic time, and many of the modern groups had representatives. A few of the more primitive or generalized types, however, still existed in the early Tertiary. Thus a toothed Bird has been found in the Eocene of England, though it is to be noted that the teeth were not set in sockets but were only dentations of the edge of the bill (Fig. 234). Another special feature was the existence of very large, flightless Ostrich-like forms which attained heights up to fully 10 feet.

Fig. 234
Head of an Eocene Bird, *Odontopteryx toliapicus*, showing teeth. (After Owen.)

Mammals. — All during the Mesozoic era Mammals existed, but they were represented only by comparatively few, small, primitive forms which always occupied a very subordinate position in the animal world. They were kept in obscurity by the dominant

and diversified Reptiles. The mighty crustal disturbance of late Mesozoic time, reaching a grand climax in the Rocky Mountain Revolution, left in its wake the end of the reign of Reptiles, and the beginning of the rule of the highly organized Mammals. Very early in the Tertiary there began a wonderful development of Mammals. Evolution of many of the higher groups went on rapidly, so that by the close of the period the Mammals had become differentiated into most of the principal modern types. One of the most significant features in the evolution of the Mammals during the Cenozoic was the gradual increase in the relative sizes of the brains. The accompanying sketches graphically illustrate this fact (Fig. 235).

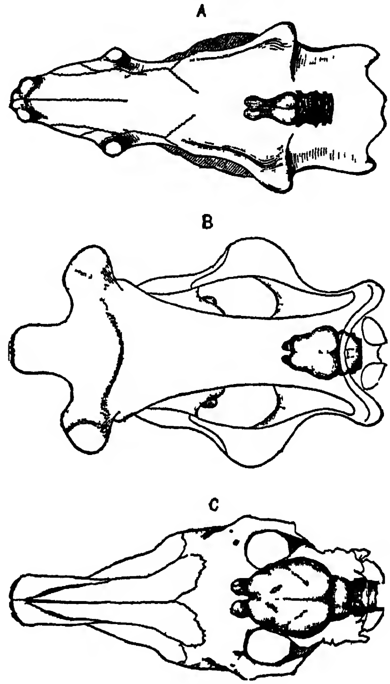


Fig. 235

Sketches to illustrate increase in size of brains of Mammals from the Eocene to the present. *A*, Eocene *Uintatherium;* *B*, Miocene *Brontotherium;* *C*, modern Horse, *Equus*. (After Marsh, from Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company.)

Mammals comprise the highest of all animals and are all characterized by suckling the young. For convenience of discussion, they may be divided into three groups as follows: (1) *Monotremes* or egg-laying forms, such as the modern Spiny Ant-eater; (2) *Marsupials* (e.g. Opossum and Kangaroo) or those giving birth to imperfectly formed young, which are then carried by the mother in a pouch (marsupium); and (3) *Placentals* (e.g. Dog, Horse, and Man) or those giving birth to well-formed young which, in the prenatal condition, are attached to the mother by the placentum. So far as known, only Monotremes and Mar-

supials existed during the Mesozoic, but during the Tertiary they were very subordinate to the Placentals, and today they are comparatively rare. The Cenozoic was (and is), therefore, very decidedly the "Age of Placental Mammals."

Because of the vast wealth of material concerning Tertiary Mammals, we can do no more, in our brief survey, than to refer to a few of the more interesting and better known evolutionary features.

Generalized Mammals of the Early Tertiary. — Although Mammals were the dominant animals even in the early Tertiary, nevertheless they were not then differentiated into the more or less clearly defined groups of today such as the *Carnivores*, or flesh eaters (e.g. Dogs, Bears, Tigers, etc.), *Perissodactyls*, or hoofed Mammals with an odd number of toes (e.g. Horses, Rhinoceroses, etc.); *Artiodactyls*, or hoofed Mammals with an even number of toes (e.g. Camels, Deer, Pigs, etc.); *Proboscidians*, or trunk-bearing hoofed Mammals (e.g. Elephants); *Rodents*, or gnawers (e.g. Rats, Squirrels, etc.); *Insectivores* (e.g. Moles, Hedgehogs, etc.); *Cetaceans*, or exclusively swimmers (e.g. Whales, Dolphins, etc.); *Primates*, or the very highest of all Mammals (e.g. Monkeys, Man, etc.); and many others. These groups, traced back toward the early Tertiary, gradually become less and less distinct until, in the Eocene, they cannot be at all distinguished as separate groups, but rather we find ancestral or generalized forms which show combinations of features of the later groups.

Fig 236

A nearly perfect skeleton of the Eocene *Phenacodus primaevus* (After Cope)

One of the most characteristic of these generalized types of the early Eocene was *Phenacodus* (see Fig. 236). The various species of this genus showed about the same range in size as modern Dogs. Each foot had five toes which were supplied with nails rather between true claws and true hoofs in structure. The simple (primitive) teeth indicate that the animal was omnivorous, that is both plant and flesh eating. In harmony with other early Tertiary Mammals, the brain was relatively small and almost devoid

of convolutions, thus pointing to a low grade of mental development.

Perissodactyls (e.g. Horse). As an example of the history of the odd-toed, hoofed Mammals, we shall consider the well-known evolution of the *Horse* family. At least forty species of this family, ranging from early Eocene to the present, have been described,

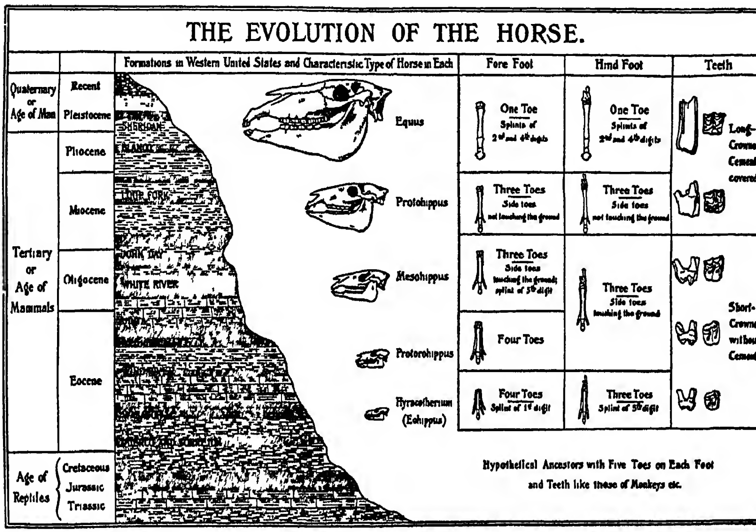


Fig. 237

Chart to illustrate the evolution of the Horse family (After W D Matthew, *Amer. Mus Nat. Hist Journal.*)

and practically every connecting link in the evolution of the family is known. Only a few of the most important changes can be noted in our brief description, which is, in fact, not much more than an explanation of the excellent chart shown in Fig. 237. The earliest form, called *Eohippus*, occurring in the lower Eocene, was about the size of a large cat (Fig. 238). On the forefoot it had four functional toes (one larger than the others) and a splint or imperfectly developed fifth toe. The hind foot had three functional toes and a splint. Doubtless this early member of the Horse family was derived from an original five-toed ances-

tor[1] whose general structure was something like Phenacodus. In the later Eocene *Protorohippus* had four distinct toes on the front foot and three on the hind foot, but with no sign of splints. This form was but little larger than Eohippus. During the Oligocene *Mesohippus* had three functional toes (the middle one being distinctly larger), with the former fourth toe reduced to a splint on

Fig. 238

Primitive or ancestral Horses, *Eohippus*, of the Eocene Restored by C R. Knight under the direction of H F. Osborn. (Permission of American Museum of Natural History)

the front foot, while the three functional toes continued on the hind foot. It was about the size of a sheep. In the Miocene *Protohippus* had three toes on both fore and hind feet, but in each case only one was large and functional, with the other two small toes not long enough to reach the ground. This form was about the size of a pony. During the Pliocene and Quaternary,

[1] More recently there has been reported the discovery of a still more primitive form, even more closely resembling the five-toed ancestor.

Equus, or the modern Horse, had, and has, one toe only on each front and hind foot with the two side toes of Protohippus reduced to mere splint bones, entirely non-functional. Thus we see that

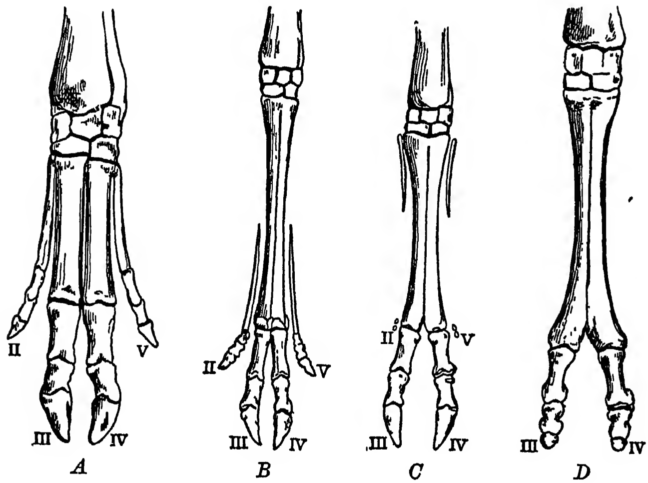


Fig 239

Evolution of foot of even-toed (Artiodactyl) Mammals illustrated by existing forms. *A*, Pig; *B*, Roebuck; *C*, Sheep; *D*, Camel. (From Norton's "Elements of Geology," by permission of Ginn and Company, Publishers)

the middle toe of the original five-toed ancestor has developed, to the exclusion of the others, and it is thought that this has tended toward greater fleetness of foot. While these evolutionary changes took place, there were also gradually developed longer and more complex teeth; the two entirely separate bones (radius and ulna) of the fore limb gradually became consolidated into a single strong bone; and the brain steadily increased in relative size.

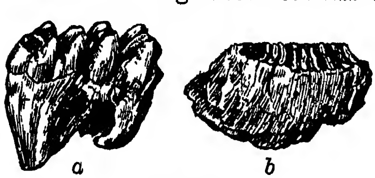


Fig 240

a, Mastodon tooth, *b*, Mammoth tooth. Both viewed from the side.

Artiodactyls (e.g. Camel). These even-toed, hoofed Mammals (Fig. 239), like the odd-toed ones, were descended from a five-toed

Eocene ancestor. In their development the first toe disappeared, while the middle pair of the remaining four became larger and the two side toes became smaller and smaller, having disappeared altogether in such a type as the modern Camel. This sort of evolution in the Camel family has been traced in almost as much detail as in the Horse family. Beside the Camel, other two-toed

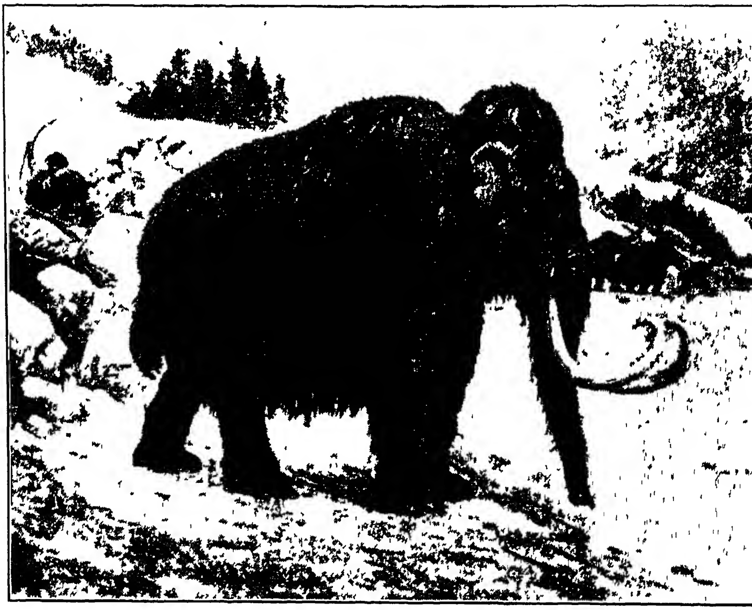


Fig 241

A Mammoth Elephant, *Elephas primigenius*, restored by C R Knight. (Permission of American Museum of Natural History)

existing forms are Deer, Cattle, and Sheep. The two-toed Artiodactyls now predominate, while the four-toed forms (at present represented e.g. by Hogs and Hippopotami) culminated in the Tertiary.

Proboscidians (e.g. Elephant). This group of hoofed Mammals, characterized by the proboscis (trunk), has been traced through many intermediate forms back to primitive Eocene ancestry. Proboscidians culminated in the Pliocene, when they

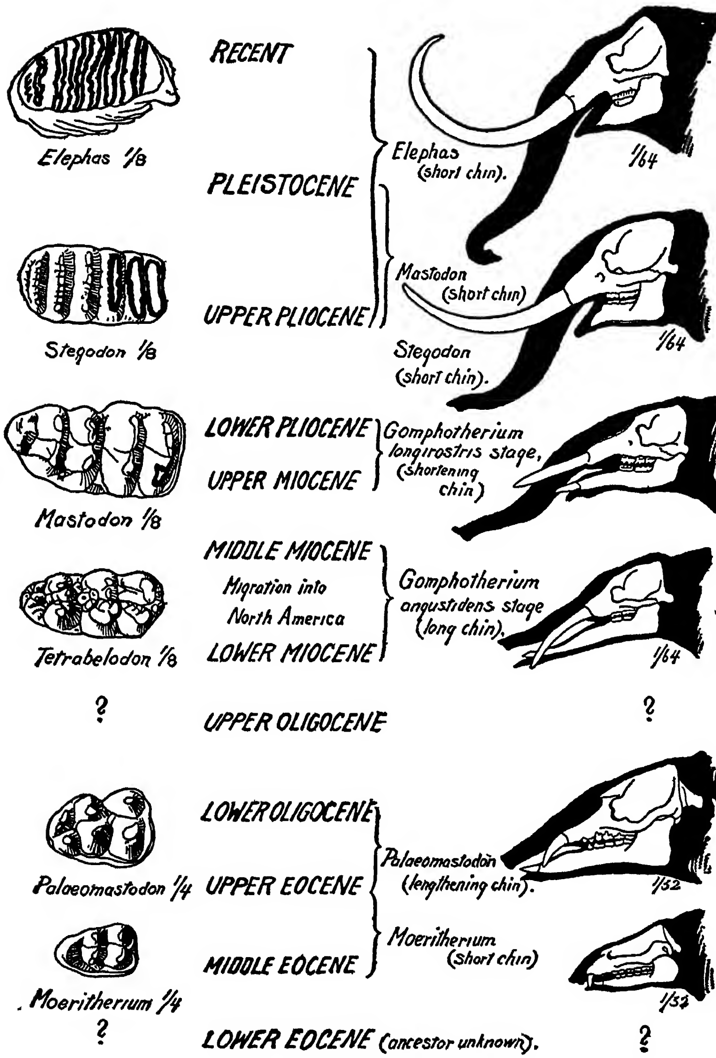


Fig 242

Chart to illustrate the evolution of the Elephants (From Scott, after Lull, modified by Sinclair, by courtesy of The Macmillan Company.)

were the largest (up to 13 or 14 feet high), the most numerous, and widespread over much of the earth except Australia. *Mastodons*, now wholly extinct, are characterized by having knob-like prominences on the chewing surfaces of their large teeth (Fig. 240a), while the true *Elephants* (including the extinct *Mammoths*) have large nearly flat grinding surfaces on their teeth (Fig. 240b). True Elephants also nearly always show greater curvature of the tusks. The Mammoth had long brown hair (Fig. 241).

The accompanying sketches (Fig. 242), together with the following excellent summary by Lull, will give a good idea of the evolution of the Proboscidians. "Increase in size and in the development of pillar-like limbs to support the enormous weight. Increase in size and complexity of the teeth and their consequent diminution in numbers and the development of the peculiar method of tooth succession. The loss of the canines and of all of the incisor teeth except the second pair in the upper and lower jaws and the development of these as tusks. The gradual elongation of the symphysis or union of the lower jaws to strengthen and support the lower tusks while digging, culminating in *Tetrabeledon* (or *Gomphotherium*) *Angustidens*. The apparently sudden shortening of this symphysis following the loss of the lower tusks and the compensating increase in size and the change in curvature of those of the upper jaw.

"The increase in bulk and height, together with the shortening of the neck necessitated by the increasing weight of the head with its great battery of tusks, necessitated the development of a prehensile upper lip which gradually evolved into a proboscis for food gathering. The elongation of the lower jaws implies a similar elongation of this proboscis in order that the latter may reach beyond the tusks. The trunk did not, however, reach maximum utility until the shortening jaw, removing the support from beneath, left it pendant, as in the living Elephant." [1]

Carnivores (Tigers, Dogs, etc.). These modern flesh-eaters can be traced back to a generalized order or group (so-called *Creodonts*, Fig. 243) which had certain characters suggesting the Insect-eaters, hoofed Mammals, and Marsupials, as well as the Carnivores. These Creodonts or ancestral flesh-eaters had small, simple brains and many small teeth. In the course of evolution the existing carnivorous families have been derived from them.

[1] R. S. Lull: *Amer Jour. Sci*, Vol. 25, 1908, pp. 11–13.

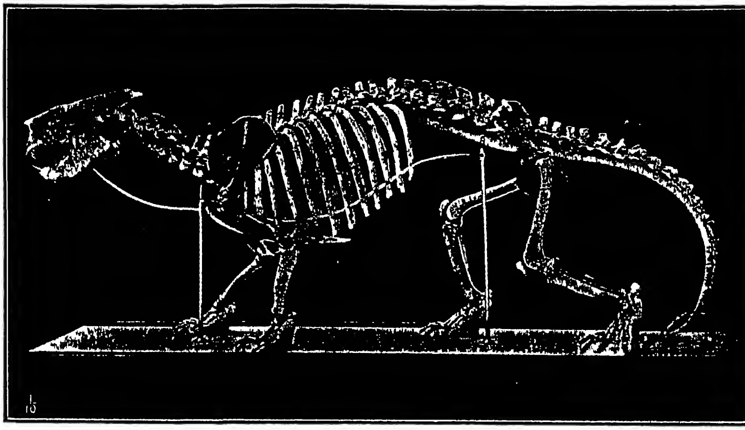


Fig 243

Skeleton of an Eocene Creodont, *Patriofelis*. (After Osborn, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

Rodents (Rats, Porcupines, Squirrels, etc.). The Rodents (gnawers) can be traced back to the early Eocene, when the incisor teeth were just developing a structure suitable for gnawing. By the middle of the Eocene the Rodents were common and their incisors were highly specialized for gnawing. Primitive Squirrel-like forms are known from the late Eocene.

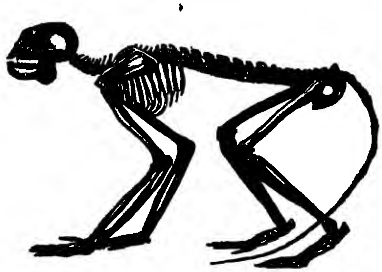


Fig 244

One of the earliest Monkeys, *Mesopithecus pentelici*, from the Miocene of Europe, restored by Gaudry Length of specimen, about 20 inches.

Insectivores (e.g. Moles, Hedgehogs, etc.). These have also been traced back to the Eocene, and, like the Rodents, they still show many of their ancestral or primitive features. They have changed much less than most of the other classes of Mammals.

Cetaceans (e.g. Whales, Porpoises, etc.). In our study of Mesozoic Reptiles we found that certain forms took to the sea

and became truly marine Fish-like creatures, such as the Ichthyosaur and the Mosasaur. So in the Tertiary (even in the Eocene) certain Mammals became so adapted to the water environment as to become Fish-like forms, such as Whales, Porpoises, etc., which are often popularly regarded as true Fishes. Apparently we have here an example of retrogression in evolution, because true land animals took to the water and their legs degenerated into swimming paddles. Certain Whale-like forms (Zeuglodons) of the Eocene reached lengths up to 60 or 80 feet and must have been extremely abundant, their vertebræ often being found in great numbers in Alabama and other places.

Lemuroids (e.g. Lemurs) and *Primates* (e g. Monkeys, Apes, and Man). These two groups include the highest of all animals. During the Eocene "Numerous Lemuroids and primitive types of Monkeys swarmed in the trees" (W. B. Scott). True Monkeys and Apes, however, did not appear till in the Miocene (Fig. 244). A partial skeleton, known as *Pithecanthropus erectus*, discovered in Java (1891) in deposits possibly of Pliocene age, has been the cause of much discussion. This creature appears to have had characters intermediate between the lowest types of Men and the highest types of Apes, but the bones have elicited much difference of opinion. By some they are regarded as those of an ancestral type of Man; by others as those of an abnormal human being; and by still others as those of a large Ape.

So far as present knowledge goes, we have no positive evidence that Man appeared on the earth even late in the Tertiary, though future discoveries may trace his ancestry that far back. The antiquity of Man will be further discussed toward the close of the next chapter.

CHAPTER XIX

THE QUATERNARY PERIOD

By the very nature of the case, our usual method of discussion cannot be applied to the Quaternary period without considerable modification, the characteristic feature having been vast sheets of ice covering much of the northern hemisphere. Otherwise the earth had reached essentially its present geological condition.

Origin of Name, Subdivisions, Etc.

As pointed out toward the beginning of the last chapter, the terms "Tertiary" and "Quaternary" are both remnants of an old geological nomenclature, and both have entirely lost their original significance. The Quaternary is the last great period of earth history, the study of which leads us right up to present-day geographic and geologic conditions. During this period nearly all of the existing species of invertebrates and lower Vertebrates, as well as most of the existing species of Mammals, had appeared. Except in the glaciated regions, the line of separation between the Tertiary and the Quaternary is not at all clearly defined.

Following the usual method, we shall divide the Quaternary period into (1) the *Pleistocene* or *Glacial* epoch, which represents the time of ice occupation of northern North America and northern Europe, and (2) the *Recent* or *post-Glacial* epoch or time since the removal of the ice from those continents. We are living in the Recent epoch.

The Fact of the Ice Age

The Quaternary period was ushered in by the spreading of vast ice sheets over much of northern North America and northern Europe. This event must take rank as one of the most interesting and remarkable occurrences in geological time. On first thought, the existence of such vast ice sheets seems unbelievable, but the Ice age occurred so short a time ago that the records of the event are perfectly clear and conclusive. The fact of this great Ice age was discovered by Louis Agassiz in 1837, and fully announced

before the British Scientific Association in 1840. For some years the idea was opposed, especially by advocates of the so-called iceberg theory. Now, however, no important event of earth history is more firmly established and no student of the subject ever questions the fact of the Quaternary Ice age.

Some of the proofs for the former presence of the great ice sheets are as follows: (1) Polished and striated rock surfaces which are precisely like those produced by existing glaciers, and which could not possibly have been produced by any other agency; (2) glacial boulders or "erratics," which are often somewhat rounded and scratched, and which have often been transported many miles from their parent rock ledges; (3) true glacial moraines, especially terminal moraines, like that which extends the full length of Long Island and marks the southernmost limit of the ice sheet there; (4) the generally widespread distribution, over most of the glaciated area, of heterogeneous glacial debris (so-called "drift") both unstratified and stratified, which is clearly transported material and typically rests upon the bed-rock by sharp contact. In regions which have not been glaciated, it is quite the rule to find that the underlying fresh rock grades upward through rotten rock into soil.

Ice Extent and Centers of Accumulation

The best known existing ice sheets are those of Greenland and Antarctica, particularly the former, which covers about 500,000 square miles. This glacier is so large and deep that only an occasional high rocky mountain projects above its surface, and the ice is known to be slowly moving outward in all directions from the interior to the margins of Greenland. Along the margins, where melting is more rapid, some land is exposed, but often the ice flows out into the ocean, where it breaks off to form large icebergs.

The accompanying map Fig. 245 shows the area of nearly 4,000,000 square miles of North America covered by ice at the time of maximum glaciation, and also the three great centres of accumulation and dispersal of the ice. The directions of flow of the ice from these centres have been determined by the study of the directions of a very large number of glacial striæ, as well as the direction of transportation of the glacial debris. Greenland was also buried under ice during the Quaternary period.

Two striking features regarding the distribution of the ice were (1) the failure of the ice to cover any of Alaska except its high southern mountain region, though that country is much farther north than most of the glaciated area; and (2) the failure of any-

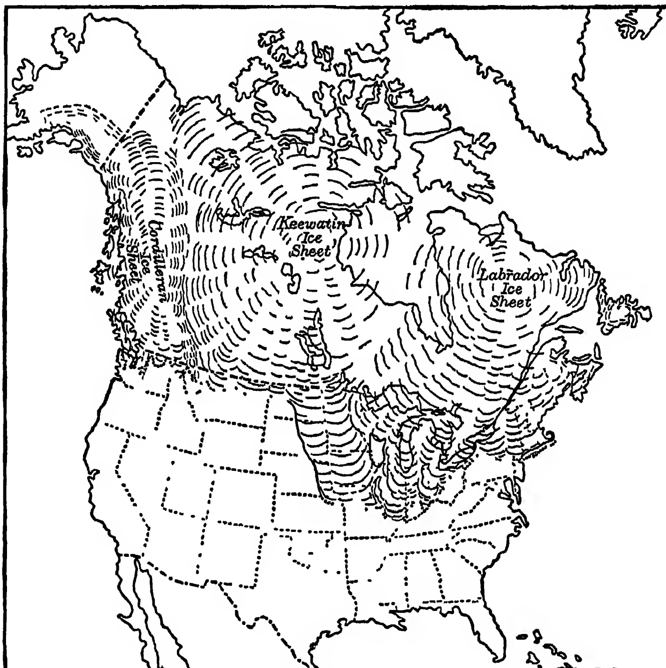


Fig. 245

Map showing the areas occupied by ice in North America at the time of maximum glaciation. The three great centres of dispersal are indicated. (After Salisbury, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

thing like continuous ice sheets over the high plateaus of the western United States, while the great ice sheet spread over much of the low plains area of the upper Mississippi Basin.

From its centre of accumulation, the Labradorean ice sheet extended fully 1600 miles southwestward or to about the mouth of the Ohio River. The Keewatin sheet extended from its centre

southward nearly as far, or into northern Missouri. These two great ice sheets practically merged. "One of the most marvelous features of the ice dispersion was the great extension of the Keewatin sheet from a low flat centre westward and southwestward over what is now a semiarid plain, rising in the direction in which the ice moved, while the mountain glaciers on the west, where now known, pushed eastward but little beyond the foothills" (Chamberlin and Salisbury).

Fig 246

Glaciated surface of granite high up on the side of a deep canyon Middle Fork of King's River near Paradise Valley, California (Photo by the author)

The Cordilleran ice sheet appears to have been mostly made up of both plateau and typical mountain (Alpine) glaciers. Toward the south it extended only a little way over the high mountains of the northwestern United States.

Newfoundland, and possibly also Nova Scotia, had local centres of glaciation.

South of the ice sheets above described, the higher mountains of the United States, even as far south as southern California, Arizona, and New Mexico, bore numerous glaciers greatly varying in size (Fig. 246). These were always of the typical valley or Alpine types instead of ice sheets. Some of these mountains, such as Shasta, Hood, Rainier, and those of the Glacier National Park in Montana, still have glaciers, the greatest being those of Mount Rainier, where they attain lengths of from 4 to 6 miles.

Direction of Movement and Depth of Ice

The fact that glacial ice flows as though it were a viscous substance is well known from studies of present-day glaciers in the

Alps, Alaska, and Greenland. A common assumption, either that the land at the centre of accumulation must have been thousands of feet higher, or that the ice must have been immensely thick, in order to permit flowage so far out from the centre, is not necessary. For instance, if one proceeds to pour viscous tar slowly in one place upon a perfectly smooth (level) surface, the substance will gradually flow out in all directions, and at no time will the tar at the centre of accumulation be very much thicker than at other places. The movement of the ice from each of the great centres was much like this, only in the case of the glacier the piling up of snow and ice was by no means confined to the centres of accumulation.

Some of the finest examples of the influence of topography upon the direction of movement of the ice are afforded by New York state on account of its peculiar relief features. When the Labradorean ice sheet spread southward as far as northern New York, the Adirondack Mountains stood out as a considerable obstacle in the path of the moving ice, and the tendency was for the current to divide into two portions, one of which passed southwestward up the low, broad St. Lawrence Valley, and the other due southward through the deep, narrow Champlain Valley. As the ice kept crowding from the rear, part of the St Lawrence ice lobe pushed into the Ontario basin, while another portion worked its way up the broad, low Black River Valley and finally into the Mohawk Valley. At the same time the Champlain ice lobe found its way into the upper Hudson Valley, and sent a branch lobe westward up the broad, low Mohawk Valley. The two Mohawk lobes, the one from the west and the other from the east, met in the midst of the Mohawk Valley. As the ice sheet continued to push southward, all the lowlands of northern New York were filled; a tongue or lobe was sent down the Hudson Valley; and finally the whole state, except slight portions of the southern border, was buried under the ice. The general direction of flow at this time of maximum glaciation was southward to southwestward, with perhaps some undercurrents determined by the larger topographic features. Thus we learn that the major relief features of the state very largely determined the direction of ice currents, except at the time of maximum glaciation, when only the undercurrents were controlled. These ideas are abundantly borne out by the distribution of glacial striæ and boulders over the state.

Evidences of glaciation, such as striæ, boulders, lakes, etc.,

occur high up in the Adirondacks, the Catskills, the Green and the White Mountains, and the Berkshire Hills, so that the greatest depth of ice over New York and New England could not have been less than one or two miles. In fact we have every reason to believe that all of the mountains named, except possibly the Catskills, were completely buried. The reader may wonder how the ice over a mile thick in northern New York could have thinned out to disappearance at or near the southern border of the state, but observations on existing glaciers show that it is quite the habit of extensive ice bodies to thin out very rapidly near the margins, thus producing steep slopes along the ice fronts.

There is little reason to doubt that the vast ice sheet over the upper Mississippi Valley was also thousands of feet thick. The positions of the moraines there clearly prove that the ice front was more or less distinctly lobate.

Successive Ice Invasions

The front of the great ice sheet, like that of ordinary valley glaciers, must have shown many advances and retreats. In the

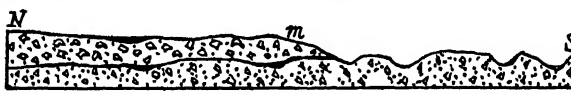


Fig. 247

Diagram to show how successive glacial drift sheets are distinguished. *N* to *m*, younger drift; *m* to *S*, surface of older drift Surface of younger drift almost unaffected by erosion and weathering, while the older drift is notably dissected and its surface considerably weathered A distinct terminal moraine at *m* marks end of younger drift sheet. Heavy black bands represent deposits of organic matter.

northern Mississippi Valley, however, we have positive proof of several (perhaps five or six) important advances and retreats of the ice which gave rise to true interglacial stages. The strongest evidence is the presence of successive layers of glacial debris, a given layer often having been oxidized, eroded, and covered with vegetation before the next (overlying) layer was deposited (see Fig. 247). In drilling wells through the glacial deposits of Iowa, for example, two distinct layers of vegetation are often encountered at depths

of from 100 to 200 feet. Near Toronto, Canada, plants which actually belong much farther south in a warm climate have been found between two layers of glacial debris. Thus we know that some, at least, of the ice retreats produced interglacial stages with warmer climate and were sufficient greatly to reduce the size of the continental ice sheet or possibly to cause its entire disappearance.

By applying the principles just laid down, at least five advances and retreats of the ice, with distinct interglacial intervals have been recognized in North America as follows: (1) Pre-Kansan or Jerseyan; (2) Kansan; (3) Illinoian; (4) Iowan; and (5) Wisconsin.[1]

In New York and New England no very positive evidence has as yet been found to prove truly multiple glaciation, though some phenomena as, for example, certain buried gorges, are difficult to account for except on the basis of more than one advance and retreat of the ice. At any rate there appears to be no good reason whatever to believe that there were more than two advances and retreats of the ice over this region.

For our purpose in considering only the general effects of glaciation, we may practically disregard the problem of multiple glaciation, because the final effects would have been essentially the same as a result of a single great glacial advance and retreat.

The Driftless Areas

In southwestern Wisconsin, and extending a little into Iowa and Illinois, there is a non-glaciated area of about 10,000 square miles which lies several hundred miles north of the southern limit of the ice sheets (see Fig. 245). This is called a "driftless area," because of the utter absence of glacial debris or any other evidence of glaciation within its boundary. In spite of several ice invasions on all sides, this small area was never ice covered. Residual soils and rotten rock are widespread; there are no lakes; and the streams are mostly graded and without waterfalls or rapids. This small region, therefore, gives an excellent idea of the kind of topography which the whole upper Mississippi Valley would have shown had it not been for the glaciation. At no time did the Labradorean ice sheet spread far enough westward,

[1] The Wisconsin invasion is sometimes divided into two — an early and a late Wisconsin.

or the Keewatin sheet far enough eastward, to cover this driftless area. The highland district just south of Lake Superior doubtless served to deflect and weaken the flow of the Labradorean ice which otherwise might have spread far enough to have covered the driftless area.

A much smaller driftless area has more recently been discovered along the Mississippi River in Missouri. It is not difficult to understand why such an area so close to the southern limit of glaciation escaped all advances of the ice sheets.

Ice Erosion

Ice, like flowing water, has very little erosive effect unless it is properly supplied with tools. When flowing ice is shod with hard

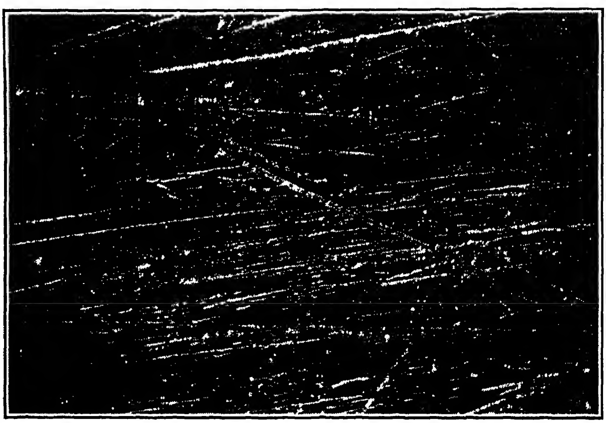


Fig 248

Smoothed and striated (glaciated) limestone.
(Photo by the author)

rock fragments the power to erode is often pronounced, because the work of abrasion is mostly accomplished by the rock fragments embedded in the ice rather than by the soft ice itself. For instance, when the great ice lobe moved up the St. Lawrence Valley it was shod with many pieces of hard pre-Cambrian rocks, and the effects of erosion are remarkably well shown in the Thousand Islands region, where successions of great grooves cut in the solid rock

may often be seen. A little search will reveal polished and scratched or grooved rock surfaces in almost any part of the glaciated region of the continent (Fig. 248). Hard rock ledges most frequently exhibit glacial marks, and the freshness and hardness of such surface rock proves that the ice eroded all of the deep residual soil as well as the zone of rotten rock, and an unknown amount of live or fresh rock.

In former years a very great erosive power was ascribed to flowing ice, but today some glacialists consider ice erosion to be almost negligible, while many others maintain that, under favorable conditions, flowing ice may produce very notable erosive effects. During the long pre-Glacial time, rock decomposition must have progressed so far that rotten rock, including soils, had accumulated to considerable depths, as today in the southern states. Such soils are called "residual," because they are derived by the decomposition of the very rocks on which they rest. But now one rarely sees rotten rock or soil in its original position well within the glaciated area, because such materials were nearly all scoured off by the passage of the great ice sheet, mixed with other soils and ground up rock fragments, and deposited elsewhere. Such are called transported soils. Along the southern side of the glaciated area, where the erosive power of the ice was least, rotten rock is more common. Ice, shod with hard rock fragments and flowing through a deep, comparatively narrow valley of soft rock, is especially powerful as an erosive agent, because the tools are supplied, the work to be done is easy, and the increased depth of the ice where crowded into a deep, narrow valley causes greater pressure on the bottom and sides of the channel. Many of the valleys of northern New York were thus favorably situated for ice erosion, as, for example, the Champlain, St. Lawrence, Black River, Finger Lakes valleys. The writer has made a special study of ice erosion in the Black River Valley of New York, and Fig. 249 is a structure section across it showing the rock terraces and the relations of the various rock formations. The conditions for ice erosion there were unusually favorable, because the ice, in its great sweep around the Adirondacks, was heavily shod with hard rock fragments and entered the deep valley by striking with greatest force against the soft rocks on the west side. The soft shales were worn back more than the harder limestones, while the very hard pre-Cambrian rocks were but little affected. If soft shales had

made up the valley bottom, ice erosion would have caused considerable deepening, as was, no doubt, the case in the valleys of the Finger Lakes region of western New York. Even in places so favorably situated as those just mentioned there is no reason to believe that ice erosion did any more than to modify the profiles of the pre-Glacial channels.

It is also a singular fact that glacial deposits left by one ice sheet may actually have been overridden by a later advance of ice with little erosion of even such soft material. This probably

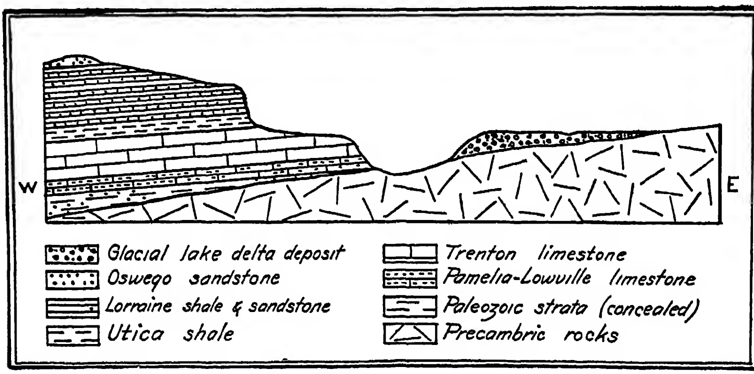


Fig 249

Structure section across the Black River Valley of northern New York to illustrate the effect of ice erosion and glacial lake deposition. Note the steep front of the shale terrace which has been produced by ice erosion, and the conspicuous delta deposit of the extinct glacial lake on the east side The surface of the delta deposit represents the former lake level (After W J. Miller, N. Y State Mus, Bul. 135.)

happens only near the margin, where the ice is rather thin and hence would not be expected to have much erosive power.

In conclusion we may say that while many comparatively small, local features were produced by ice erosion, the major topographic features of the great glaciated area were practically unaffected by the abrasive effects of the passing ice sheets.

Ice Deposits

The vast amount of debris transported by the great ice sheet was carried either on its surface, frozen within it, or pushed along

beneath it. It was heterogeneous material ranging from the finest clay, through sand and gravel, to boulders of many tons' weight. The deposition of these materials took place during both the advance and retreat of the ice, but chiefly during its retreat. Most of the deposits made during the ice advance were obliterated by ice erosion, while those formed at the time of the retreat have been left intact except for the small amount of post-Glacial erosion and weathering. The term "drift," applied to all deposits of glacial origin, was given at a time when they were regarded as flood or iceberg deposits. Drift covers practically all of the glaciated region except where bare rock is actually exposed, and its thickness is very variable, ranging from nothing to some hundreds of feet.

The ice sheet could advance only when the rate of motion was greater than the rate of melting of the ice front, and vice versa in case of retreat. Thus it is true, though seemingly paradoxical, to assert that the ice was constantly flowing southward even while the ice front was retreating northward. Whenever, during the great general retreat, the ice front remained stationary because the forward motion was just counterbalanced by the melting, all the ice reaching the margin of the glacier dropped its load to build up a *terminal moraine*. Such a moraine is a more or less distinct ridge of low hills and depressions consisting of very heterogeneous and generally unstratified debris, though at times waters emerging from the ice caused stratification. The depressions are usually called *kettle-holes*. The so-called great terminal moraine marks the southernmost limit of the ice sheet, and is wonderfully well shown by the ridge of low, irregular hills extending the whole length of Long Island. It is also more or less clearly traceable across the United States, where it marks the southernmost limit of glaciation. Terminal moraines farther northward are generally not so long or sharply defined, though many have been located and described. These are either terminal moraines found at the southernmost limits of ice sheets which did not extend as far south as earlier sheets, or *recessional moraines* formed during each considerable pause of a waning or northward retreating ice sheet.

When the ice front paused for a considerable time upon a rather flat surface, the debris-laden streams emerging from the ice formed what is called an *overwash plain* by depositing layers of sediment over the flat surface. An excellent illustration of such an overwash

plain is all of that part of Long Island lying just south of the great terminal moraine, and known as the Jamaica plain toward the west.

When the ice front extended across a more rugged country, with valleys sloping away from the ice, the large glacial streams, heavy laden with debris, caused more or less deposition of material on the valley bottoms often for many miles beyond the ice front. Such deposits, known as *valley trains*, are especially well developed along many of the larger south-flowing streams of the glaciated area.

Fig. 250

Typical drumlins (side view) in western New York (After H L Fairchild, N. Y State Mus., Bul 111)

Glacial boulders (*erratics*) have already been referred to. They are simply blocks of rock or boulders from the top of the ice or within it which have been left strewn over the country as a result of the melting of the ice. They vary in size from small pebbles to those of many tons' weight, and are naturally most commonly derived from the harder and more resistant rock formations. Thus erratics from the Adirondack Mountains are very numerous from central to southern New York. Erratics are often found high up on the mountains, where they have sometimes been left stranded in remarkably balanced positions.

A very extensive glacial deposit, called the *ground moraine*, is simply the heterogeneous, typically unstratified debris from the bottom of the ice which was deposited, sometimes during the ice advance, but most often during its melting and retreat. When it is mostly very fine material with pebbles or boulders scattered through its mass, it is known as *till* or *boulder clay*. The pebbles

or boulders of the till are commonly faceted and striated as a result of having been rubbed against underlying rock formations.

Another type of glacial deposit of unusual interest is the *drumlin*, which is in reality only a special form of ground moraine material. The typical drumlins of western New York, Wisconsin, and western Massachusetts are low, rounded mounds of till with elliptical bases and steeper slopes on the north sides. Their long axes are parallel to what was the direction of ice movement (see Fig. 250). In height they rarely exceed 200 feet, being most often

Fig 251

A group of kames in New York state (From Norton's "Elements of Geology," by permission of Ginn and Company, Publishers)

less than 100 feet. The origin of the drumlins has not yet been satisfactorily determined, though it is known that they formed near the margin of the ice either by the erosion of an earlier drift layer or by accumulation beneath the ice under peculiarly favorable conditions, as perhaps along longitudinal crevasses or fissures. Two of the finest and most extensive exhibitions of drumlins in the world are in New York, between Syracuse and Rochester, and in eastern Wisconsin, where thousands of them rise above the general level of the plains and give rise to a unique topography.

Another type of glacial deposit in the low hill form is the *kame*, which, in contrast with the drumlin, always consists of stratified drift. Kames are seldom as much as 200 feet high, and typically they have nearly circular bases, though frequently they are of

very irregular shapes. At times they exist as isolated hills or in small groups (Fig. 251), while often they are associated with the unstratified deposits of the moraines. When grouped, deep depressions occur between the hills to form what is called the knob and kettle structure. Kames were formed at or near the margin of the retreating ice, and so are found in all parts of the glaciated area, but more especially where there is considerable relief, as in New York and New England. They most generally are located in valley bottoms, but sometimes on hillsides or even hilltops. They are especially abundant along the line of the great terminal moraine (e.g. Long Island) and along the lines of the more important recessional moraines. They were formed as deposits by debris-laden streams emerging from the margin of the ice, the water sometimes having risen like great fountains because of pressure. Such deposits are now actually in process of formation along the edge of the great Malaspina glacier of Alaska.

During the ice retreat *glacial lakes* were numerous, particularly where the north-sloping valleys were dammed by the ice thus ponding the waters in the valleys. Some materials were directly deposited from the glacier in those lakes, but more was brought in by debris-laden streams flowing from the land already freed from the ice. Such glacial lakes and their deposits were common and of unusual interest, but they will be described under a subsequent heading.

In conclusion we may say that the deposition of glacial materials, like glacial erosion, has not changed the major topographic features of the glaciated region. The general tendency of ice deposits has been to fill, or partially fill, depressions and thus to diminish the ruggedness of the topography.

The Loess Deposits

Loess deposits are widespread over much of the region from eastern Nebraska, across Iowa, Illinois, and Indiana. Its distribution is rather largely independent of topography. Typically it is a soft, buff to yellowish-brown, very fine grained, sandy clay which seldom shows signs of stratification. Its thickness usually varies from 10 to 100 feet. Where eroded or cut into, the loess exhibits a remarkable tendency to stand in perpendicular cliffs, sometimes with suggestions of a sort of columnar structure. For this reason

it was once known as the Bluff formation. It is remarkably free from coarse materials, except for certain carbonate of lime and oxide of iron concretions and fossils, the latter being chiefly shells of land Gastropods. Most of the loess was deposited during the Iowan Glacial stage, because it rests upon the eroded and weathered surfaces of older glacial deposits and often passes under the later or Wisconsin deposits.

The question as to whether the loess was of aqueous or eolian origin has long been discussed. "In part the loess seems to have been washed from glacial waste and spread in sluggish glacial waters, and in part to have been distributed by the wind from plains of aggrading glacial streams" (W. H. Norton).

Great Lakes History

The Great Lakes certainly did not exist before the Ice age, but instead the depressions in that region were occupied by stream channels. During the very long erosion period from the Paleozoic to the Cenozoic, no lakes of any consequence could have persisted. Compared with such an immense length of time lakes are, at most, only ephemeral features of the earth's surface because they are soon destroyed either by being filled with sediments, or by having their outlets cut down, or both. Since the Great Lakes are of post-Glacial origin it is, then, proper to ask how they came into existence. During pre-Glacial time broad valleys were cut out along belts of weak rock in the Great Lakes region, and these old valleys, to a considerable extent at least, account for the present depressions, but not for the closed lake basins. This idea of pre-Glacial stream valleys is not at all opposed by the fact that some of the lake bottoms are now well below sea level, because there has been notable subsidence of the region since pre-Glacial time. The surface of Lake Erie is 573 feet, and its deepest point 369 feet, above sea level, while the surface of Lake Ontario is 247 feet above, and its deepest point is 491 feet below, sea level. The greatest depth (738 feet) of Lake Ontario is well toward the east end not far from the south shore, and if we consider this deep place as due to pre-Glacial erosion, we ought to find an outlet channel. But no such outlet channel exists because the whole east end, at least, of the lake is rock-rimmed. As Tarr has said: "There could hardly be a valley over 700 feet deep and broad enough to form the

continuation of the pre-Glacial Ontario Valley, which is so completely obscured by drift that not the least trace of it has been found on the surface."[1] To assume that this deep part of the basin was formed by warping of the land is not borne out by examining the exposed strata on all sides. It therefore seems quite certain that the pre-Glacial Ontario depression was considerably

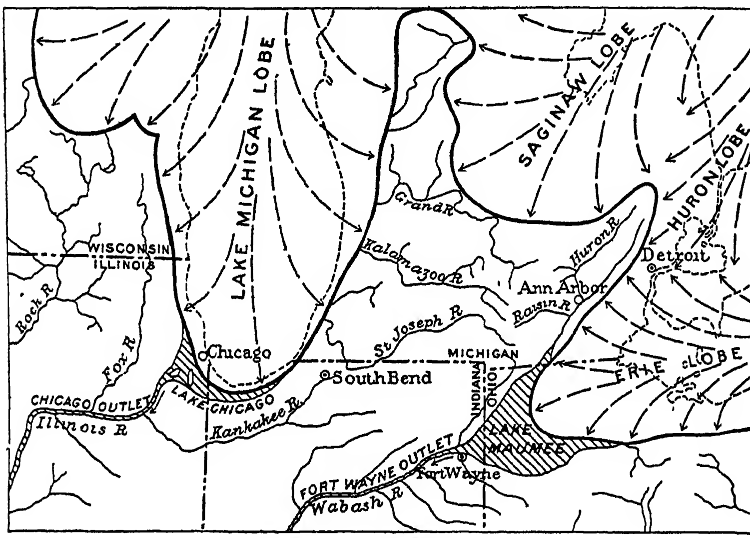


Fig 252

First stage in the history of the Great Lakes Note the small ice-front lakes (Maumee and Chicago). (After U. S. Geological Survey.)

deepened by ice erosion. The conditions were very favorable for such erosion because the rocks were chiefly soft Ordovician shales; because the ice flowed through a deep pre-Glacial valley; and because there was an unusual crowding of the ice into this valley due to pronounced deflection of a great ice current around the Adirondacks on the west side. Strong arguments might be adduced to show that by ice erosion portions, at least, of all the lake basins were appreciably deepened. Even so, however, we have not yet accounted for the present closed basins. Probably the two most

[1] R. S. Tarr· *Physical Geography of New York State*, p. 235.

important phenomena which have contributed to the formation of the closed basins of the Great Lakes are (1) the great drift accumulations along the south side and (2) the tilting of the land downward on the north side of the region. The deep drift deposits must certainly have been very effective in damming up the south or southwest-flowing pre-Glacial streams of the region. A great dumping ground of ice-transported materials from the north was in general along the southern side of the Great Lakes and south-

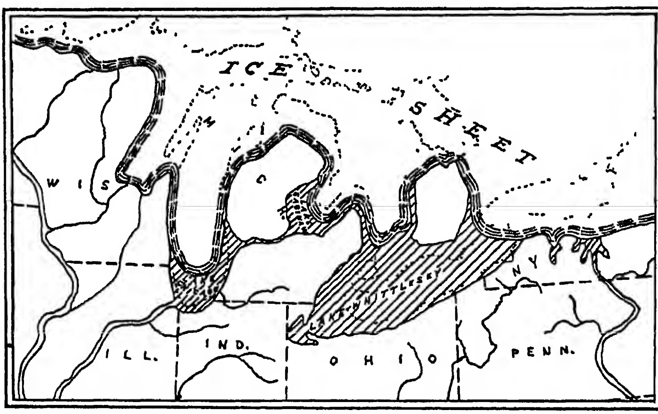


Fig 253

Lake Whittlesey stage of the Great Lakes history, when the eastern and western ice-margin lakes combined with outlet past Chicago. (After Taylor and Leverett, redrawn by W. J M.)

ward. Late in the Ice age the land on the northern side of the Great Lakes region was lower than it is today, as proved by the tilted character of certain well-known beaches of extinct lakes (see below). Such a differential tilting or warping of the land must have helped to form the closed basins by tending to stop the southward or southwestward drainage from the region. To summarize, we may say that the present Great Lakes basins are due to a combination of factors, the more important of which were: (1) the formation of pre-Glacial valleys by stream erosion; (2) a more or less deepening of these valleys by ice erosion; (3) the great accumulation of glacial debris along the southern side of the Lake district;

and (4) the tilting of the land relatively downward toward the north.

We are now ready to trace out the principal stages in the history of the Great Lakes region during the final retreat of the great ice sheet. When the ice front had receded far enough northward to uncover the southern end of Lake Michigan, and an area west of the present end of Lake Erie, small lakes were formed against the ice walls (see Fig. 252). The first of these has been called Lake Chicago, which drained past Chicago through the

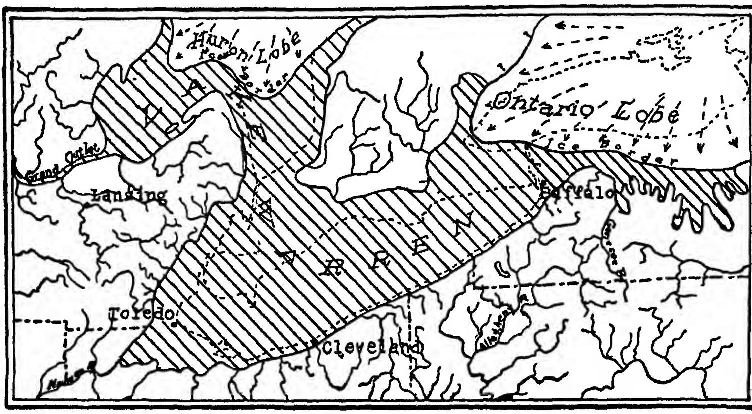


Fig 254

Glacial Lake Warren At this stage the discharge of the lake was still westward to Lake Chicago, while the eastern end of the lake covered most of the Finger Lakes region of New York. (Modified by W. J. M., after Taylor and Leverett.)

Illinois River and into the Mississippi; and the second, Lake Maumee, which drained southwestward past Fort Wayne through the Wabash River and thence into the Ohio and Mississippi.

At a later stage the conditions shown on map Fig. 253 existed. Lake Chicago was then larger, and Lake Maumee had expanded into the extensive Lake Whittlesey, which covered nearly all of the area of Lake Erie as well as some of the surrounding country. Lake Whittlesey was at a lower level than the former Maumee, and the outlet past Fort Wayne ceased, but the drainage from Whittlesey was westward by a large river flowing through small Lake

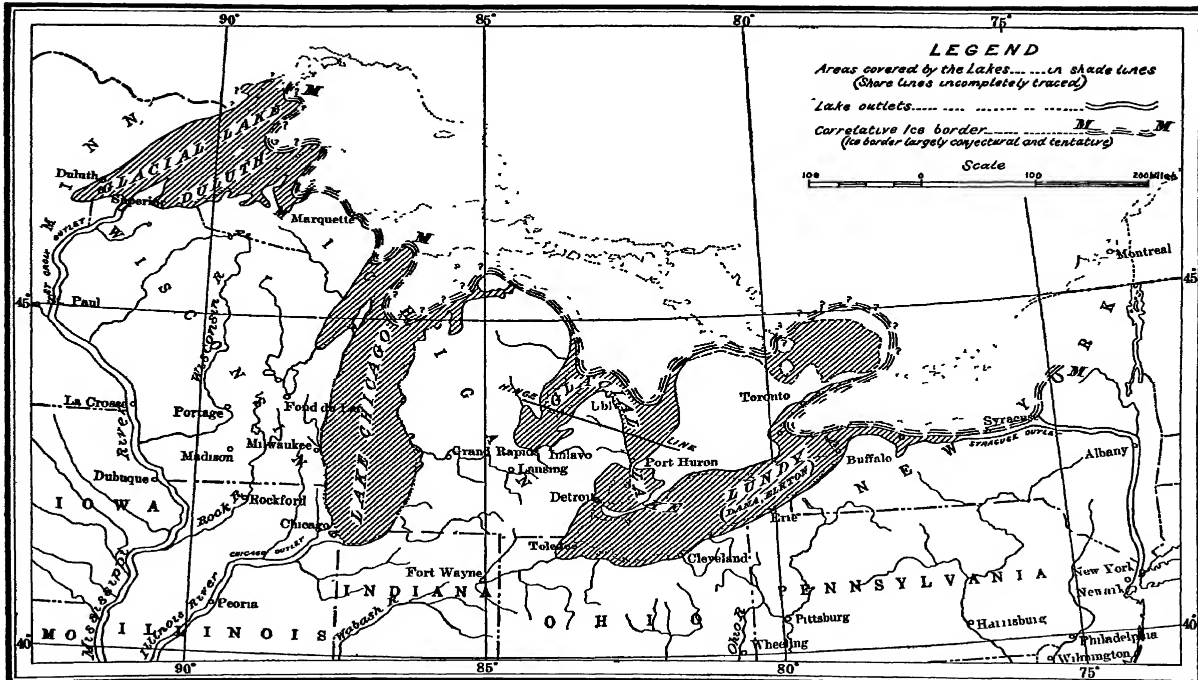


Fig. 255

Glacial Lakes Duluth, Chicago and Lundy. Note the drainage of the western lakes into the Mississippi River, and the eastern lakes into the Hudson Valley. (After Taylor and Leverett, courtesy of The Smithsonian Institution.)

Saginaw and into Lake Chicago, which latter still emptied through the Illinois River.

At a still later stage (Fig. 254) Lake Saginaw merged with the waters of the Erie Basin to form the large Lake Warren which extended along the ice front eastward nearly to central New York. As the map clearly shows, the Finger Lakes Basins of New York were then occupied by Warren waters, while Niagara Falls were not then in existence, because that region was also covered by Lake Warren. Lake Warren continued to discharge westward until a very late stage followed by the Lake Lundy level (see Fig. 255), when the waters had worked their way along the border of the Ontario ice lobe into the Mohawk Valley of New York, which was then occupied by a large glacial lake (held up by the Ontario ice lobe on the west and the Champlain-Hudson lobe on the east), and then into the Hudson Valley. Thus, for the first time, the Great Lakes drainage passed eastward into the Atlantic Ocean. This great volume of water draining eastward was often in the form of distinct streams with the ice front for north wall and the high land of the Helderberg escarpment for wall on the south. Many of these glacial stream channels, often high up on the hills of central to western New York, are still plainly visible.

By successive stages, due to complete removal of ice from central New York, and a draining of the glacial lake in the Mohawk Valley, the waters fell below the Warren-Lundy levels and Lake Iroquois was formed (see Fig. 256) The old beach line of this lake is still plainly visible in New York. Lake Iroquois covered somewhat more than the present area of Lake Ontario, and the distinctly lower water level here than in the Erie Basin allowed the modern Niagara River to begin its history by flowing northward over the limestone plain near Buffalo. Meantime the waters of the upper lake basins had merged to form Lake Algonquin, which at first probably discharged past Detroit through the Erie Basin and into Lake Iroquois by way of Niagara River. Later, however, when the ice had withdrawn a little farther northward, a lower outlet was formed through the Trent River by which Lake Algonquin drained into Lake Iroquois. The old Trent River channel is now higher than the Detroit outlet, but some of the proofs for the former Trent outlet are as follows: (1) The presence there of a large, distinct river channel; (2) the convergence of the beaches

toward that channel; and (3) the fact that the land was then considerably lower on the north or northeast side of Lakes Ontario and Erie than on the south side. For example, in following the old Iroquois beach we find that it gradually rises to higher levels until it is several hundred feet higher at the east than near the mouth of Niagara River. This tilting of the beach has been due to warping of the land since the lake existed, and it is evident therefore that during the Algonquin-Iroquois stage the Trent River channel was lower than that past Detroit. During the

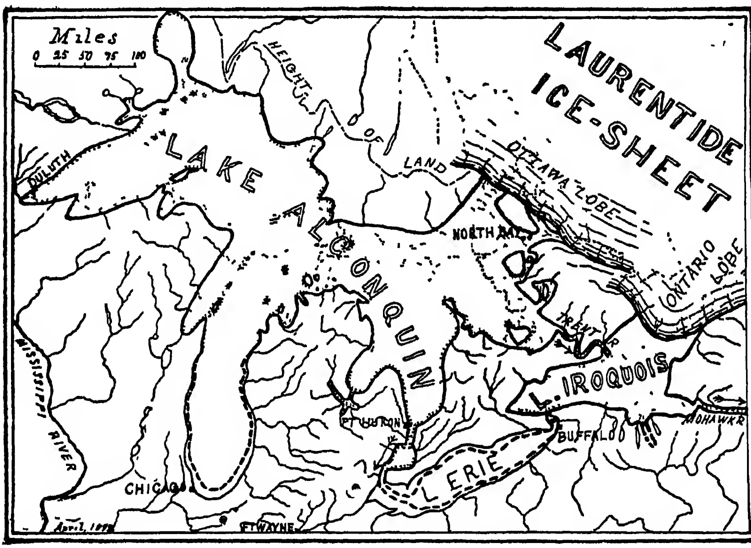


Fig. 256

The Algonquin-Iroquois stage of the Great Lakes, with outlet through the Mohawk-Hudson Valleys of New York. (After Taylor, courtesy of the New York State Museum)

Algonquin-Iroquois stage the waters of all the Great Lakes region discharged through the Mohawk-Hudson valleys, and the volume of water which flowed through the Mohawk Valley must have been as great as, if not greater than, that which now goes over Niagara Falls. During this time the St. Lawrence Valley was still buried under ice.

Still later the ice withdrew enough to allow the Algonquin-

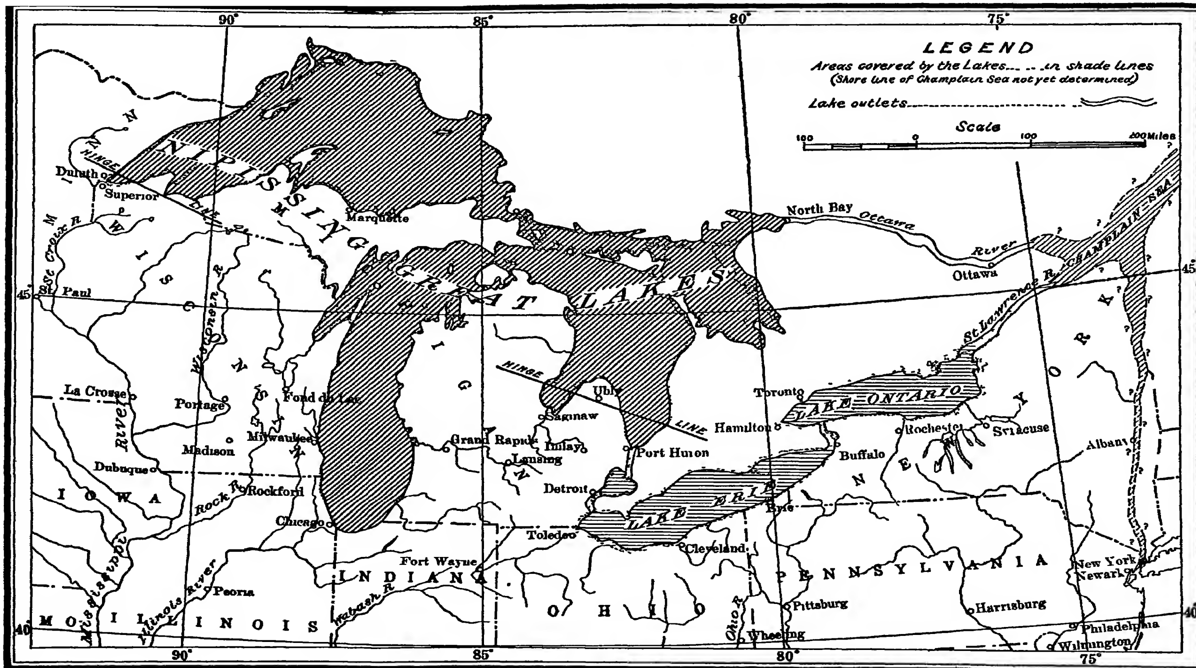


Fig. 257

The Nipissing Great Lakes and their correlatives. The oblique-lined area on the east was occupied by tide-water (Champlain sea), but the boundary lines are not yet very definitely known. (After Taylor and Leverett, courtesy of The Smithsonian Institution.)

Iroquois waters to discharge along the northern base of the Adirondacks and into what appears to have been ice-ponded waters in the Champlain Basin, and thence into the Hudson Valley. The Mohawk Valley outlet was thus abandoned.

Finally the ice withdrew far enough to free the St. Lawrence Valley when the waters of the Great Lakes region dropped to a still lower level, bringing about the Nipissing Great Lakes stage (see Fig 257). The Nipissing Lakes found a low outlet through the Ottawa River (then free from ice) and into the Champlain arm of the sea. Post-Glacial warping of the land brought the Great Lakes region into the present condition, but this, and the Champlain subsidence, being really post-Glacial features, will be described below.

Other Existing Lakes and Their Origin

Counting all, from the smallest to the largest, there are within the glaciated area of North America tens of thousands of lakes, and these constitute one of the most striking differences between the geography of the present and that of pre-Glacial time. These lakes are widely scattered, though in the United States they are most abundant in the regions of greater relief, such as Maine, New Hampshire, New York, and Minnesota, because lake basins were more readily formed by drift dams across the deeper pre-Glacial valleys of those regions

It is well known that most of the larger lakes, especially those of the linear type, occupy portions of pre-Glacial stream channels. All the existing lakes are due, either directly or indirectly, to glacial action. Among the ways by which such bodies of water may be formed are these: (1) by building dams of glacial drift across old river channels; (2) by ice erosion; and (3) by accumulation of water in the numerous depressions which were formed by irregular deposition of the drift (kettle-holes, etc.). Hundreds of small lakes, often not more than mere pools in size, belong to the last named type, while very many of the large and small lakes are due chiefly to the existence of drift dams. Certain lakes in southeastern Canada and elsewhere appear to occupy rock basins scoured out by ice erosion.

In considering the origin of glacial lakes, the so-called Finger Lakes of central-western New York deserve special mention. All

are agreed that the lakes of this remarkable group occupy pre-Glacial valleys, most of which, at least, contained north-flowing streams. These lakes have dams of glacial drift across their lower (north) ends, and the dams have been important factors in the formation of the lakes, being in some cases perhaps the sole cause. But in the cases of the two largest lakes — Seneca and Cayuga — there is strong evidence, from the hanging valley character of the tributaries, that the pre-Glacial valleys were notably deepened by ice erosion.

The presence of Lake Champlain is due principally to a combination of factors, including late elevation of the land, with greater uplift on the north; heavy glacial accumulations toward the north; and possibly some deepening as a result of ice erosion.

In the basin of Lake George there was a pre-Glacial divide where the "Narrows" are now located, and this divide appears to have been considerably lowered by ice erosion when part of the Champlain ice lobe ploughed its way through the deep, narrow valley. The waters are now held in by drift dams at each end.

Well within the glaciated region of the interior of the continent the history of Lake Winnipeg is of special interest, but since this lake is merely a remnant of a former much larger body of water, it will be described in connection with extinct glacial lakes.

Extinct Glacial Lakes

The beds of thousands of extinct glacial lakes are known to be scattered over the glaciated area. Some of these existed only during the time of the ice retreat, while others persisted for a greater or lesser length of time after the Ice age. Lakes Warren, Iroquois, etc., already described, were fine examples of the first type. North-sloping valleys were particularly favorable for the development of glacial lakes during the retreat of the ice, because the ice front always acted as a dam across such valleys, thus causing the waters to become ponded. Among the best criteria for the recognition of these extinct glacial lakes are typical, flat-topped, delta deposits formed by inflowing streams and distinct beaches.

A good example of the many glacial lakes which existed only when the waning ice sheet was present, acting as a dam to pond the waters, was Lake Warrensburg, situated in the southeastern Adirondack region of New York. This lake, which lay in parts

of the Hudson and Schroon River valleys, was remarkably long (70 miles) and narrow (see map Fig. 258). Delta terraces and wide sand flats, marking the bed of the former lake, are finely preserved. These deposits are several hundred feet higher at the north than at the south because of post-glacial tilting of the land of the general region. The map shows the approximate position of the ice-border dam when the Lake George and Lake Champlain basins were still occupied by the glacier. Several remnants of the glacial lake still remain as shown by the dotted areas within the ruled areas.

A fine example of a very large glacial lake in the interior of North America, and now represented only by remnants (e.g. Lake Winnipeg), has been called Lake Agassiz in honor of the discoverer of the fact of the Quaternary Ice age. This lake, fully 700 miles long and several hundred miles wide, extended over the whole valley of the Red River of the North in North Dakota and Minnesota, and

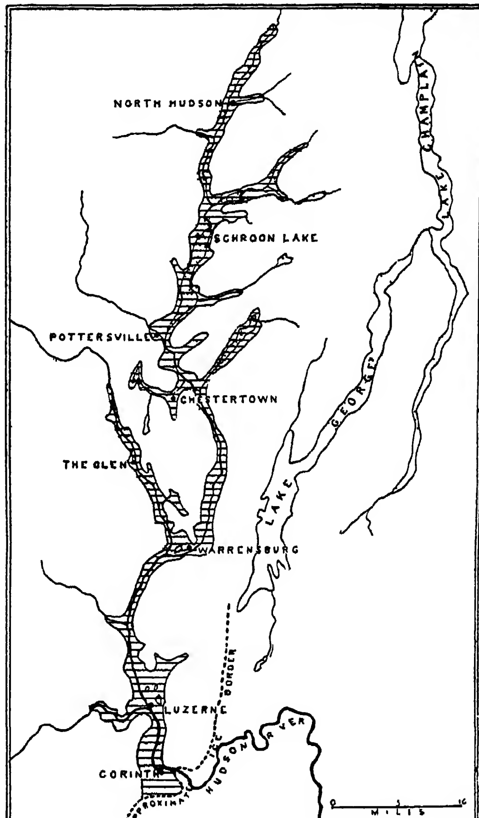


Fig. 258

Glacial Lake Warrensburg in the southeastern Adirondack Mountains of New York The position of the border of the glacier, which acted as a dam, is indicated (After W J Miller, Bul. Geol Soc. Amer, Vol. 36, 1925.)

northward over much of Manitoba. It covered a larger area than the combined Great Lakes. Its water was held up by the united fronts of the Keewatin and Labradorean ice sheets as they retreated northward. Its outlet was southward through the Minnesota and Mississippi rivers until the ice melted back (northward) far enough to open the outlet by way of Nelson River to Hudson Bay, when the great body of water was rapidly lowered,

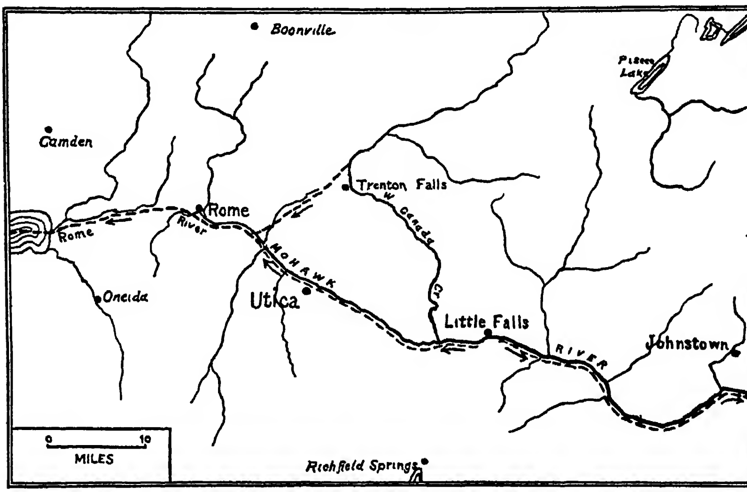


Fig 259

Sketch map of central New York, showing the relation of the pre-Glacial drainage to that of the present Pre-Glacial drainage shown by dotted lines only where essentially different from existing streams (By W J M, based on work by A P Brigham)

leaving only the present-day remnants, principally Lake Winnipeg. The soil of this smooth old lake bed is wonderfully rich.

Drainage Changes Due to Glaciation

In addition to its lakes, the glaciated area is also characterized by numerous gorges and waterfalls, which are largely due to glaciation. As a result of the very long time of pre-Glacial erosion, it is certain that typical, steep-sided, narrow gorges, as well as waterfalls, must have been very uncommon, if present at all.

Like lakes, such features are ephemeral, because, under our conditions of climate, gorges soon (geologically) widen at the top, and waterfalls disappear by retreat or by wearing away the hard rock which causes them.

Changes of stream courses are also numerous in many parts of the glaciated territory It is the present purpose to describe only a few typical, well-studied cases of such stream changes

From the standpoint of both geology and human history, the gorge at Little Falls (on the New York Central R.R.) in central New York is the most important in that state. Before the Ice age there was a divide instead of a gorge several hundred feet above the present river level. The Mohawk River flowed eastward, and the now extinct Rome River flowed westward from that divide (see Fig. 259). During the Algonquin-Iroquois stage of the Great Lakes history, those lakes discharged through the Mohawk Valley and across the Little Falls divide. It was the passage of this great volume of water over the divide

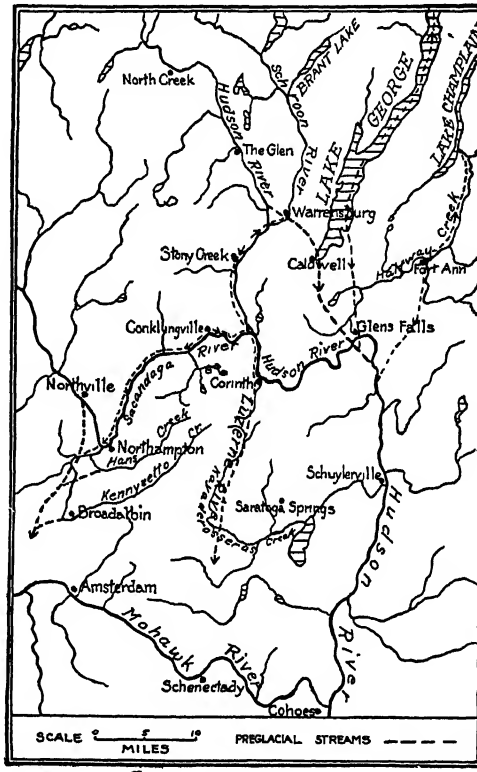


Fig. 260

Sketch map of the southeastern Adirondack region, showing the relation of the pre-Glacial drainage to that of the present Pre-Glacial courses shown by dotted lines only where essentially different from present streams (After W. J. Miller, Bul Geol Soc Amer, Vol 22)

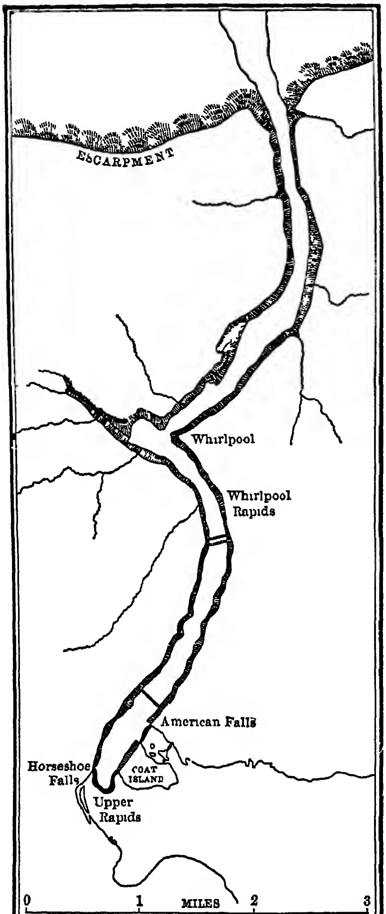


Fig 261

Sketch map of the Niagara River gorge (Modified after Gilbert, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers)

which caused the cutting of most of the gorge as we now see it, except for the narrow trench in the hard, low-lying rock, which is no doubt due to post-Glacial erosion. During the gorge cutting, aggradation (building up by sediments) of the valley bottom took place westward from Little Falls, so that the drainage from Rome, N. Y., was able to continue eastward even after the disappearance of Lake Iroquois. Thus we have here an excellent illustration of exact reversal of drainage due to glaciation, and by this means the upper waters of the present Mohawk River were added to what was the pre-Glacial Mohawk.

In the southeastern Adirondack Mountains certain important principles of drainage changes due to glaciation are illustrated by the upper waters of the Hudson River. The accompanying sketch map (Fig. 260) gives an idea of the changes. Near Warrensburg the Hudson River was deflected westward from its pre-Glacial channel because of the presence of a lobe of the waning ice sheet in the Lake George depression. At Corinth and Northampton, respectively, the Hudson and Sacandaga rivers show remarkable eastward deflections

instead of following broad, deep pre-Glacial valleys southward into the Mohawk Valley. These deflections were caused by heavy morainic deposits acting as dams across the valleys south of Corinth and Northampton.

The world-famous Niagara Falls and gorge are wholly post-Glacial in origin. After plunging 167 feet at the falls, the river rushes for 7 miles through the gorge, whose depth is between 200 and 300 feet. When the glacial waters in the eastern Great Lakes region had dropped to the Iroquois level, the Niagara limestone terrace in the vicinity of Buffalo and with steep escarpment or northern front at Lewiston and Queenston, ceased to be covered with lake water, and the Niagara River came into existence by flowing northward over this limestone plain. The river first plunged over the escarpment at Lewiston, thus inaugurating the falls there. Since that time the falls have receded the 7 miles up stream to their present position. Soft shales underlie the layer of harder Niagara limestone, and the recession of the falls has clearly been caused by the breaking off of blocks of limestone due to undermining of the soft shales. A glance at the map (Fig. 261) will show that the gorge development is really taking place on the Horseshoe Falls side, where the volume of water is much greater, and that

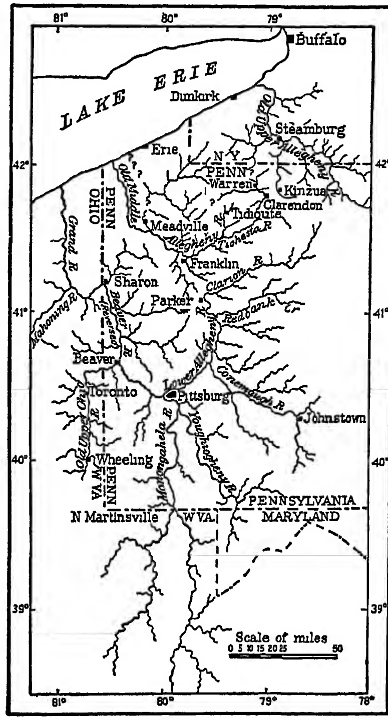


Fig 262

Pre-Glacial drainage of the upper Ohio River Basin (After Chamberlin and Leverett, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

in a short time, geologically considered, the American Falls will be dry.

The drainage of the upper Ohio River Basin has been well-nigh revolutionized as a result of glaciation. By comparing the pre-Glacial drainage map (Fig 262) with one showing present-day drainage, the principal changes will be readily understood. The pre-Glacial upper Ohio flowed northward from Beaver, Pennsylvania, instead of southward, as at present, and, between Beaver and Sharon, the direction of pre-Glacial drainage has been exactly reversed. Also, all of what is now known as the drainage area of the upper Allegheny River passed northward through two pre-Glacial streams. The drainage changes were caused by ice occupancy and deposition of heavy drift across the north-western portion of Pennsylvania.

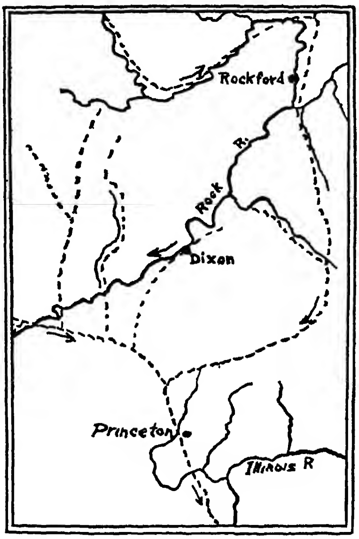


Fig 263

Pre-Glacial drainage (dotted lines) of a part of northwestern Illinois (Modified after Leverett)

Another well-studied example of important drainage change is shown by the accompanying map (Fig. 263) of part of northern Illinois. The pre-Glacial Rock River flowed southward into the Illinois River, instead of southwestward into the Mississippi as at present.

Even such large rivers as the Mississippi and Missouri were sometimes notably shifted out of their pre-Glacial channels by the invasion of the ice sheets. Thus, the Missouri River which formerly followed what is now the James River Valley in eastern South Dakota, was forced many miles westward to its present course across the state.

The above cited cases are sufficient to illustrate the general principles of drainage modifications due to glaciation, the two chief factors having been (1) actual presence of the ice or (2) heavy drift filling in pre-Glacial valleys.

ADVANTAGES AND DISADVANTAGES OF GLACIATION

Advantages. — As a result of late Tertiary stream dissection, much of what is now the glaciated area of the United States had been converted into a fairly rugged country. Because of the heavy accumulations of drift, chiefly in the depressions, this ruggedness was greatly diminished and, in fact, many districts were actually converted into almost featureless plains. Old lake beds (e.g. that of Lake Agassiz) also are usually very smooth. Thus, agricultural pursuits, transportation, and travel have been made easier.

Over very extensive areas, such as the upper Mississippi Valley, the soils have been made deeper and richer on the average because the pre-Glacial soils were not only comparatively thin on the numerous hillsides, but also they were sandy or clayey residual materials from which much of the rich (soluble) mineral plant foods had been washed out. The glacial drift soils are usually more uniformly deep and consist of finely ground rocks of many kinds still rich in the soluble plant foods.

Water-power facilities have been vastly increased because of the development of thousands of waterfalls, rapids, and lakes. Pre-Glacial streams were mostly graded and hence without waterfalls or rapids, while pre-Glacial lakes were almost entirely absent. Lakes, by acting as reservoirs, help much in causing a more uniform flow of streams. In many places such reservoir effect is furthered by artificially increasing the heights of the natural dams, as e.g. in the Adirondacks. Also many large reservoirs can easily be constructed at comparatively little expense by restoring dams of extinct lakes.

Large lakes afford cheap transportation facilities, and often have a tempering influence upon the climate. Many lakes furnish abundant water supplies for towns and cities, as well as more or less fish for food.

The benefit of lakes, waterfalls, gorges, etc., from the æsthetic or scenic standpoint would be difficult to overestimate.

Drift deposits are often used, e.g. clays, for the manufacture of brick, tile, etc., and sand and gravel for various construction purposes.

Disadvantages. — In some cases the earth's surface has been increased in ruggedness by the drift accumulations, especially in

extensive kame-moraine areas, thus hindering agriculture, transportation, and travel.

In many places, as in parts of New England, New York, and eastern Canada, the cultivation of the soil has been made difficult because of the numerous glacial boulders it contains. In these same regions many of the old lake or other deposits are too sandy or gravelly to be very fertile.

Large areas now covered by lake waters would make valuable farming land. This is particularly true of the Great Lakes.

All things considered, it seems certain that the advantages due to glaciation are notably greater than the disadvantages.

Duration of the Glacial Epoch

According to Chamberlin and Salisbury, the most important criteria for estimating the duration of the Glacial epoch include: "(1) the amount of erosion of the drift, (2) the depth of leaching, weathering, and decomposition of its materials; (3) the amount of vegetable growth in interglacial intervals, (4) the climatic changes indicated by interglacial and glacial floras and faunas; (5) the times needful for the migration of faunas and floras, particularly certain plants whose means of migration are very limited, (6) the time required for advances and retreats of the ice; and some others." A few of these, as the first, are subject to direct measurement, but most of them are matters of judgment.

The average of the estimates of five glacial geologists who have most studied the data is shown in the following table:

From the Late Wisconsin to the present	1 time unit.
From the Iowan to the present	3 to 5 time units.
From the Illinoian to the present	7 to 9 time units.
From the Kansan to the present	15 to 17 time units.
From the Sub-Aftonian (Jerseyan) to the present	X time units.[1]

"After carefully considering many points, these same authors (Chamberlin and Salisbury) offer the following table accompanied

Climax of the (Late) Wisconsin.	20,000 to 80,000 years ago
Climax of the Iowan . .	60,000 to 400,000 years ago.
Climax of the Illinoian	140,000 to 720,000 years ago.
Climax of the Kansan	300,000 to 1,360,000 years ago.
Climax of the Sub-Aftonian (Jerseyan)	Y to Z years ago.

[1] Chamberlin and Salisbury. *College Geology*, pp. 890–891.

by the statement that "little value is to be placed on estimates of this kind, except as a means for developing a conception of the order of magnitude of the time involved." [1]

Length of Time Since the Glacial Epoch

Estimates of the length of time since the close of the Ice age are perhaps more satisfactory, though it must be remembered that the close of the Ice age was not the same for all places. The ice retreated northward very slowly and when, for example, southern New York was free from the ice, northern New York was still occupied by the glacier. The best estimates of the length of time since the close of the Ice age are based upon the rate of recession of Niagara Falls. We have learned that Niagara River began its work about the time the glacial waters in the Erie-Ontario basins dropped to the Iroquois level, and that the falls were first formed by the plunging of the river over the limestone escarpment at Lewiston. Studies based upon actual surveys, drawings, daguerreotypes, photographs, etc., made between the years 1842 and 1905, have shown that the Horseshoe Fall had receded about 5 feet a year, while the American Fall, between 1827 and 1905, had receded about 3 inches a year. Thus the gorge cutting is clearly taking place on the Canadian side. The length of the gorge is 7 miles, and if we consider the rate of recession to have been always 5 feet a year, the length of time necessary to cut the gorge would be something over 7000 years. But the problem is not so simple, since we know that at the time of, or shortly after, the beginning of the river, the upper lakes drained out through the Trent River, and then still later through the Ottawa River. So it is evident that, for a good part of the time since the ice retreated from the Niagara region, the volume of water passing over the falls was notably diminished, and hence the length of time for the gorge cutting increased. The best estimates for the length of time since the ice retreated from the Niagara region vary from 10,000 to 40,000 years, an average being about 25,000 years. In a similar way, the time based upon the recession of St. Anthony's Falls, Minnesota, ranges from about 10,000 to 16,000

[1] Obviously, the determination of the number of years equivalent to one time unit involves the determination of the time since the disappearance of the last ice sheet, and this is discussed under the next heading

years. While closer estimates are practically impossible, it is at least certain that the time since the Ice age is far less than its duration, and that, for the region of the northern United States, the final ice retreat occurred only a very short (geological) time ago.

When we consider the slight amount of weathering and erosion of the latest glacial drift, we are also forced to conclude that the time since the close of the Ice age in the United States is to be measured by only some thousands of years. Thus kames, drumlins, extinct lake deltas, and moraines with their kettle-holes, have generally been very little affected by erosion since their formation.

Time Since the Climax of the Last Ice Sheet

A way to determine the number of years since the last (Wisconsin) ice sheet reached its climax is to find out how long it took the glacier to recede from its southernmost limit to Niagara Falls, or about 600 miles, and add this figure to the age of the falls.

A fair idea of the rate of recession of the last ice sheet may be gained by counting and correlating the layers of clay which were deposited in lakes in front of the retreating edge of the glacier. Each layer, consisting of a darker and a lighter band, is called a *varve*. Each varve represents the material laid down in one year, the lighter, coarser portion during the summer, and the darker, finer grained portion (colored with organic matter) during the winter. By the use of this method, De Geer found that the last ice sheet in Europe retreated a distance of 270 miles to the northwest of Stockholm in 5000 years, or at the rate of 285 feet per year. Antevs,[1] using the same method, concluded that the last glacier receded a distance of 185 miles in western New England in 4100 years, or at the rate of about 240 feet per year. If, therefore, we put the rate of retreat at about 260 feet per year, it took the Wisconsin ice sheet somewhat more than 12,000 years to retreat from its southernmost limit to Niagara Falls. Combining this figure with the average estimate of 25,000 years for the age of Niagara, we get at least a rough approximation of the time since the last (or Wisconsin) glacier reached its climax, or about 37,000 years ago.

[1] E Antevs. *The Recession of the Last Ice Sheet in New England*, 1912, p. 90.

Cause of the Glaciation

The cause of the glaciation has been a very perplexing problem. Various hypotheses, often of widely different character, have been offered by way of explanation, but there is nothing like general agreement on the subject We have here a fine illustration of the difference between "fact" and "hypothesis" which the student of natural science must always keep clearly in mind. Thus, the fact of the Glacial epoch (including much of its history) is conclusively established, but the cause of the glaciation is a matter concerning which we have only hypotheses or speculations.

In this elementary work we can do no more than suggest several of the leading hypotheses. Those further interested in the subject are referred to special articles and larger general works, particularly Chamberlin and Salisbury's "Geology," Vol. 3. One point to be borne in mind is that no hypothesis is required to account for an average yearly temperature of more than 10 or possibly 12 degrees lower than at present over the glaciated area in order to have brought on the Ice age.

A Geologic (Elevation) Hypothesis. — As we have already pointed out, the evidence, chiefly from the submerged river channels along the Atlantic Coast, clearly indicates greater altitude of northeastern North America late in the Tertiary and probably also in the early Quaternary. An altitude of from 4000 to 5000 feet greater than now has been claimed for this region. Since it is well known that the temperature becomes lower with increasing altitude (one degree for about 300 feet), it has been argued that the greater altitude of the glaciated area was in itself sufficient cause for the glaciation. "Northern elevation produced ice-accumulation; ice-accumulation by weight produced subsidence; subsidence produced moderation of temperature and melting of ice; and this last by lightening of load produced re-elevation" (J. Le Conte). It is not necessary to assume that maximum elevation and ice-accumulation were coincident, because an effect often lags behind its cause. This northern elevation also is believed to have sufficiently upraised the northern ocean basins to cut off warm currents, like the Gulf Stream, thereby depriving the northern lands of such warming influences.

It has been urged against this hypothesis that there is no posi-

tive evidence for nearly as much as 4000 to 5000 feet of elevation of the glaciated region; that it is not at all proved that the northern elevation occurred at the proper time to produce glaciation; and that the only way glacial and interglacial stages could be accounted for would be by the unreasonable assumption of repeated elevation and subsidence corresponding to each advance and retreat of the ice.

Croll's Astronomic Hypothesis.[1] — According to Croll, as excellently interpreted by Le Conte, the glaciation was caused by "the combined influence of precession of the equinoxes and secular changes in the eccentricity of the earth's orbit. By the former — viz., precession — winter, which in the northern hemisphere occurs now when the earth is nearest the sun (perihelion), is gradually in 10,500 years brought round so as to occur when the earth is farthest off from the sun (aphelion) (Fig. 264). The effect of this, it is claimed, would be to make longer and colder winters, and shorter but hotter summers in the northern hemisphere, such as now occur in the Antarctic regions. By the latter — viz., increasing eccentricity (which forms a much longer cycle) — these effects, which are now small on account of the nearly circular form of the earth's orbit, would become very great. At the time of greatest eccentricity, the earth would be 14,000,000 miles farther off from the sun in winter than in summer, the winter would be twenty-two days longer and 20° colder, and the summers twenty-two days shorter, but much hotter than now. . . . Now, according to Croll, the

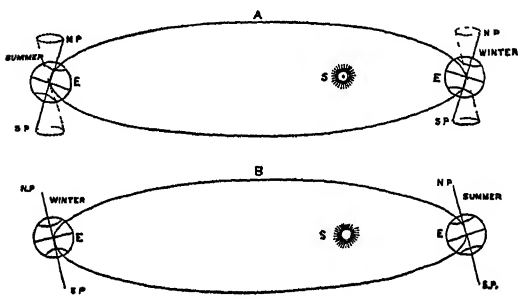


Fig 264

Diagram showing effect of Precession: *A*, present condition; *B*, condition 10,500 years hence. Eccentricity much exaggerated. (After Le Conte's "Geology," permission of D Appleton and Company.)

[1] For a fuller statement of this hypothesis see Croll's *Climate and Time in Their Geological Relations*, 1890.

coincidence of aphelion winter, with a period of greatest eccentricity produces a glacial climate "[1]

As a result of the astronomic relations, Croll held that the heat equator, with the trade winds zone, must have been shifted farther away from the glaciated hemisphere with consequent shifting of direction of warm ocean currents. Thus, during the Quaternary Glacial epoch, the Gulf Stream must have been diverted southward by the eastern point of South America.

According to Croll's hypothesis (1) there must have been many Glacial epochs during the earth's history; (2) alternations of cold and warm stages (seven or eight) must have occurred during the Glacial epoch, (3) these cold and warm stages alternated between northern and southern hemispheres; and (4) the Quaternary Glacial epoch in the northern hemisphere began 240,000 years ago, lasted 160,000 years, and declined 80,000 (or possibly 60,000) years ago.

At present we have positive evidence for five or six times of glaciation during geologic history and still more may be discovered.[2] Also it has been proved that there were five, and probably six, ice advances and retreats corresponding to colder and warmer stages during the Quaternary Glacial epoch. As regards the duration of this Ice age and the time since its close, it seems impossible to imagine seven or eight advances and retreats of the ice within 160,000 years unless we postulate rates of advance and retreat much greater than studies of existing glaciers show. Also the best geological evidence does not place the close of the Ice age so far away as 60,000 to 80,000 years. One of the most serious objections to Croll's hypothesis is the fact that, during the Permian period, there was widespread glaciation in comparatively low latitudes (20° to 35°) either side of the equator.

Chamberlin's Atmospheric Hypothesis.[3] — Among the atmospheric hypotheses, the one which Chamberlin has put into its best form "is based chiefly on a postulated variation in the constituents of the atmosphere, especially in the amount of carbon

[1] J Le Conte: *Elements of Geology*, 5th ed, pp. 613–614.

[2] It should of course be remembered that the proper temperature conditions for glaciation may have recurred many times when other factors such as requisite precipitation of snow may not have obtained, and hence great ice sheets may not actually have formed.

[3] For a fuller treatment of this hypothesis see Chamberlin and Salisbury's *Geology*, Vol. 3, pp. 432–446.

dioxide and water Both these elements have high capacities for absorbing heat, and both are being constantly supplied and constantly consumed. . . The great elevation of the land at the close of the Tertiary seems to afford conditions favorable both for the consumption of carbon dioxide in large quantities,[1] and for the reduction of the water content of the air. Depletion of these heat-absorbing elements was equivalent to the thinning of the thermal blanket which they constitute. If it was thinned, the temperature was reduced, and this would further decrease the amount of water vapor held in the air. The effect would thus be cumulative. The elevation and extension of the land would also produce its own effects on the prevailing winds and in other ways, so that some of the features of the Hypsometric (elevation) hypothesis form a part of this hypothesis. . . . By variations in the consumption of carbon dioxide, especially in its absorption and escape from the ocean, the hypothesis attempts to explain the periodicity[2] of glaciation. Localization (of glaciation) is attributed to the two great areas of permanent low pressure in proximity to which the ice sheets developed "[3]

Huntington's Sun-spot Hypothesis. — It seems to be a well-established fact that the temperature of the air near the earth's surface is lower at times of unusual sun-spot activity. Huntington has suggested that the several real glacial epochs of known geological time may have occurred during periods of very exceptional sun-spot activity, probably in combination with certain other factors. During such a cycle of very intense solar activity, not only would the earth's winds be stronger and hence conduct more heat upward from the earth's surface, but also these stronger winds would cause the great eastward moving storm areas (or cyclonic storms) to travel farther north than they do at present in both North America and Europe. The lowering of the temperature and the increase in atmospheric moisture, resulting from the conditions just mentioned, would explain the gathering of the great Pleistocene glaciers.

In conclusion we may say that, as is true of so many other great natural phenomena, no one hypothesis or explanation is

[1] Much carbon dioxide is used up in the decomposition or carbonation of the rocks

[2] That is, the successive advances and retreats of the ice sheets.

[3] Chamberlin and Salisbury: *College Geology*, pp. 898–899.

sufficient to account for all the features of glacial epochs. Probably several or all, or at least parts of several or all, of the above hypotheses must be properly combined in order to explain the phenomena of glaciation, and hence it is more readily understood why great glacial epochs have not been more common throughout the history of the earth.

Post-Glacial (Recent) History of the Glaciated Area

We have already shown that, about the beginning of the Glacial epoch, the north Atlantic Coast region at least was much higher than it is today, positive proof for this being afforded by the submerged lower Hudson, St. Lawrence, and other channels which must have been cut when the land was higher. Toward the close of the Glacial epoch, and shortly after, we know that the land was relatively lower even than it is today. It was during this time of subsidence (sometimes called the Champlain epoch) that the lower Hudson and St. Lawrence channels were submerged and the seacoast was transferred to more nearly its present position. But the land being even lower than now, the lowlands of Long Island and in the vicinity of New York City were under water and a narrow arm of the sea extended through the Hudson and Champlain Valleys to join a broad arm of the sea which reached up the St. Lawrence Valley and possibly even into the Ontario Basin (see Fig. 257). This so-called Champlain Sea existed at the time of the Nipissing stage of the Great Lakes already described. Champlain Sea beaches, containing marine shells and the bones of Walruses and Whales, have been found at altitudes of about 400 feet near the southern end of Lake Champlain, 500 feet at its northern end, and 600 or more feet at the eastern end of Lake Ontario. In the lower Hudson Valley the deposits of this age are about 70 feet above sea level, and at Albany a little over 300 feet. The altitudes of these so-called raised beaches show how much lower the land was during the time of greatest submergence, and that the subsidence was most toward the north. That this greatest submergence occurred after the close of the Ice age in this region, is proved by the fact that the now raised beaches and marine deposits rest upon the last or Wisconsin ice drift.

The most recent movement of the earth's crust in the region

under discussion was the very gradual elevation which expelled the Champlain Sea and left the land at its present altitude. The altitudes of the raised Champlain beaches show that the greatest elevation was on the north. The warping of the Iroquois Lake beaches already described occurred at this same time. Actual surveys during the past century have proved that this upward movement in the northern Great Lakes region is still progressing at the rate of 5 inches in 100 miles in 100 years.

Quaternary Conditions in the Non-Glaciated Regions

Over many parts of the continent there was deposition of sediments during Quaternary time outside of the glaciated area, but little or nothing can be done by way of correlating these with different glacial and interglacial stages because of the lack of the usual means of comparison. These deposits were of various sorts, including those of river flood-plain, wind, terrestrial, lacustrine, volcanic, and marine origin.

Atlantic and Gulf Coasts. — On the Atlantic and Gulf Coastal Plains, and in addition to the Lafayette (Pliocene?) already described, there is a well-known series of unconsolidated deposits of sands, gravels, clays, etc , usually comprised under the name *Columbia.* Like the Lafayette, the Columbia is wholly a surficial deposit but at lower altitudes, never rising more than a few hundred feet above sea level and generally less than 200 feet. On the north Atlantic Coastal Plain, at least, the Columbia is rather clearly divisible into three formations (Sunderland, Wicomico, and Talbot), each of which is represented topographically by a more or less distinct terrace with the oldest at the top.

There has been much difference of opinion regarding the origin and significance of these Columbia deposits, but they are now quite certainly known to be marine terraces. According to Shattuck,[1] each of the formations and terraces of the Columbia is explained as due to subsidence (or submergence) below sea level and deposition of sediments, followed by elevation (or emergence) and erosion. The fossil evidence regarding non-marine or marine origin of the deposits is far from conclusive.

Western United States. — Quaternary deposits, representing many types of origin, are known in the west.

[1] G B. Shattuck *Pliocene and Pleistocene,* Md Geol. Survey, p. 137.

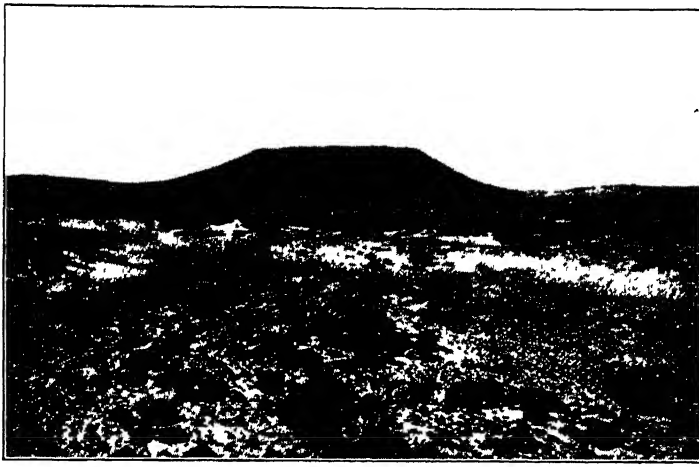


Fig. 265

A late Quaternary cinder cone on the Mohave Desert near Amboy, California (Photo by the author.)

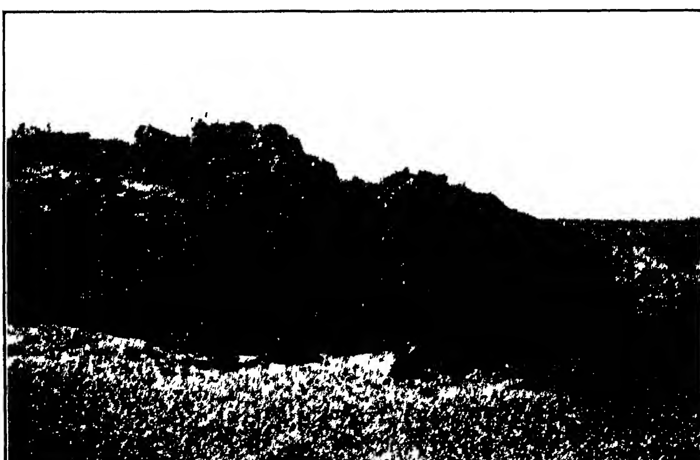


Fig. 266

An edge of a late Quaternary lava-flow on the Mohave Desert near Amboy, California. This flow is associated with the cone shown in Fig. 265 (Photo by the author)

Volcanic deposits of this age in the west are not always clearly separable from those of the Tertiary, but it is certain that rather vigorous vulcanism continued into the Quaternary. Such volcanic deposits, including lava-flows, cinders, and volcanic ashes, are

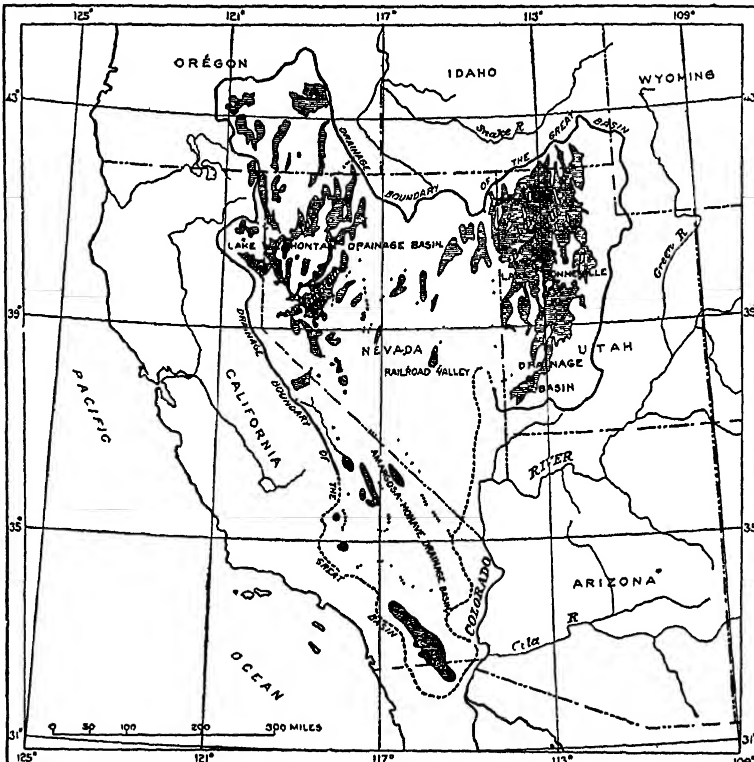


Fig 267

Map showing the extinct Quaternary lakes of the Great Basin region. (After U. S Geological Survey.)

known in New Mexico, Utah, Idaho, and all the states farther west as well as in Alaska. In southern Oregon the collapse of the upper portion of Mount Mazama, producing the basin of Crater Lake, took place after large glaciers were developed on the

sides of the mountain. Mount Shasta shows lava flows of post-Glacial or recent age, while small lava fields and cinder cones in northern and southern California and in northern Arizona must be of late Quaternary age because they are so unaffected by weathering and erosion (Fig. 265). As already mentioned in the discussion of Tertiary vulcanism, a cinder cone and small lava field have certainly been built up within the last 200 years, while Lassen Peak in northern California broke forth in 1914.

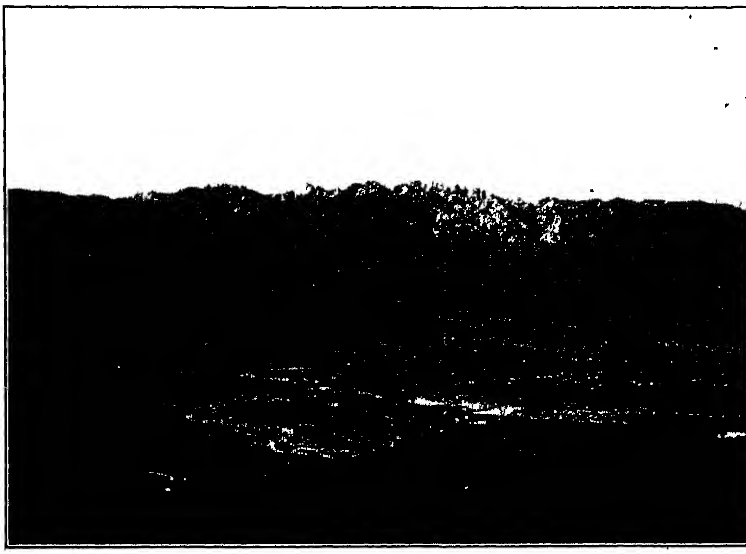


Fig. 268

Part of the great modified fault-face on the south side of the San Gabriel Mountains north of Pasadena, California These mountains were upraised mainly in earlier Quaternary time (Photo by Professor J. E. Wolff)

At the bases of mountains throughout the arid and semi-arid regions of the west, great accumulations of talus and alluvial materials took place. Some of the alluvial cones or fans have a thickness of fully a thousand feet. Extensive flood-plain deposits are found in many places.

Recent studies have shown that the wind has been, and is, a very important agent of erosion and deposition, particularly in

the arid western regions. Deep and extensive wind-blown deposits are still forming in many of the intermontane basins.

During part of the Quaternary, at least, the Great Basin region had a moister climate than at present, because lakes were much more numerous and larger than now (Fig. 267) One of the largest of these was *Lake Bonneville*, which represented a greatly enlarged stage of the Great Salt Lake. Lake Bonneville was of fresh water,

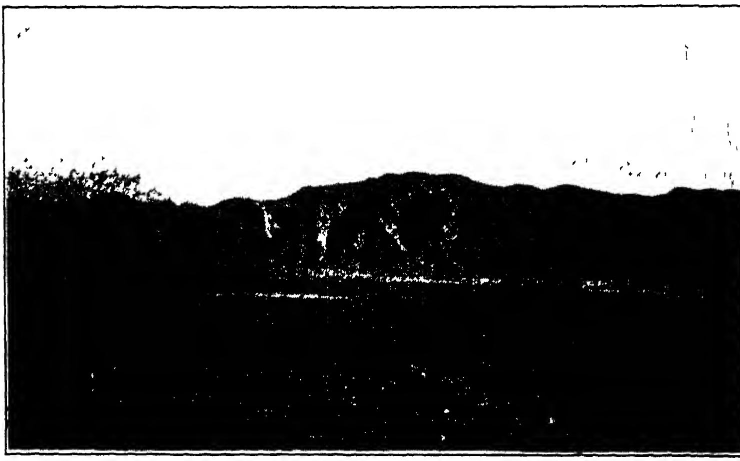


Fig 269

Great fault-facets of late Quaternary age on the side of Deep Spring Valley, California (Photo by Robert H Mansfield.)

covered 19,000 square miles; and had a maximum depth of 1000 feet. Its remnant, the present heavy brine of the Great Salt Lake, covers about 2000 square miles and has a maximum depth of only about 50 feet. The outlet of Lake Bonneville was northward into Snake River. The former existence of this great body of water is positively proved by the perfectly preserved beaches, wave-cut terraces, deltas, etc. Another very large body of water, called *Lake Lahontan*, occupied some thousands of square miles of western Nevada, but it had no outlet. Since the lowering of the water levels in these basins, crustal disturbances have caused a tilting of the old shore lines some hundreds of feet.

Locally, along the Pacific border, Quaternary fossiliferous marine deposits occur up to altitudes of 200 or 300 feet or more.

"Important and more or less widespread periods of diastrophism later than the one terminating the Monterey (middle Miocene) period of deposition occurred in the Pleistocene. . . . Minor movements producing local unconformities took place in central and southern California at various times during the Pleistocene in addition to the more far-reaching disturbances in the same epoch."[1]

The islands off the coast of southern California were connected with the mainland late in the Tertiary, or early in the Quaternary, as shown by the flora, and in one case the remains of a Mammoth. A subsidence, causing the separation of the islands from the mainland, was followed by partial re-elevation of some to the extent of at least 1000 feet, as proved by the raised sea-beaches on the mainland and on some of the islands. Raised beaches near San Francisco testify to Quaternary upward movements of 1500 to 1800 feet. Similar beaches on the northern coast of Oregon lie at 200 feet or more above the sea.

As suggested in the discussion of the Tertiary, there was more or less of a continuation of late Tertiary diastrophism throughout much of the Cordilleran region during Quaternary time, involving such as folding in the Coast Range Mountains, tilting of the great Sierra fault-block, uplift of the block mountains of southern California (Fig. 268), elevation of the Cascade platform, faulting in the Great Basin (Fig. 269), differential uplift of the Colorado Plateau, and rejuvenation in the Rocky Mountain and Great Plains regions.

The Glacial Epoch in Europe

In many important respects the history of the Quaternary period in Europe is much like that of North America. The accompanying map (Fig. 270) shows the extent (about 600,000 square miles) of the ice sheet at the time of maximum glaciation. As the map also shows, the great centre of dispersal was over the Scandinavian peninsula, with apparently a small, secondary centre over Scotland. The ice over Scandinavia is estimated to have been 6000 to 7000 feet deep. The Baltic, North, and Irish Seas were completely filled by the great ice sheet which extended well south into Germany and Russia. As in North America, five or six glacial and interglacial stages have been recognized. During the Glacial epoch, the glaciers of the Alps were far larger and more

[1] Ralph Arnold: *Outlines of Geologic History*, by Willis and Salisbury.

numerous than today, and they often flowed down to the lowlands on all sides. The Pyrenees and the Caucasus Mountains were also vigorously glaciated.

As in North America, also, northern Europe was notably higher than now, apparently late in the Tertiary or early in the Quaternary; then, toward the close of the Glacial epoch, there was subsidence (of Scandinavia at least) to below the present level; and this was followed by partial re-elevation of at least some hundreds of feet to the present level. Actual surveys have proved that from central to northern Sweden the land is still rising. The great fiords of Norway, with their raised beaches, testify to the important changes of level above mentioned.

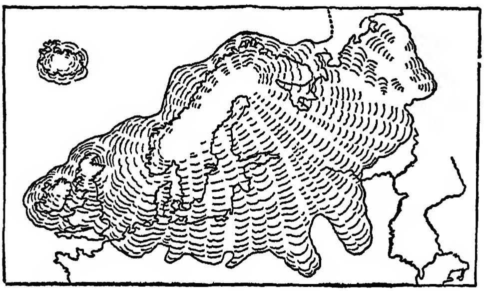


Fig 270

Map showing the extent of ice in Europe at the time of maximum glaciation. (After J Geikie, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers)

In other continents many of the higher mountains bore glaciers, even where none at all exist today. Also, so far as known, the Antarctic region was heavily glaciated much as it is today.

Life of the Quaternary

The species of plants and invertebrate animals of the whole Quaternary period were much the same as those now living; therefore we shall pass them by without special description. Among the Vertebrate animals, the species of the lower classes, such as Fishes, Amphibians, Reptiles, and Birds, were almost all the same as those now living, but in the highest class of Vertebrates (Mammals) there were important changes.

Mammals, except Man. — One of the most characteristic features of Quaternary (especially Pleistocene) Mammals was the great size of so many. In fact, as regards size and diversity of forms, the Mammals may be said to have attained their culmina-

tion during the Pleistocene epoch. Comparing the Mammals of that epoch with those of today, we find that many species, especially of the large animals, have become extinct, and the world is now (except for Man) said to be "zoölogically impoverished." The vicissitudes of the climate, i e. alternations of glacial and interglacial conditions, appear to have "produced a very severe struggle for existence and were fatal to a great many large

Fig. 271

A great Ground-sloth, *Megatherium americanum*. (After W. B. Scott, by permission of The Macmillan Company)

Mammals, causing numerous extinctions over the larger part of the world" (W. B. Scott). It is our present purpose to refer to only a few of the most interesting now extinct Pleistocene Mammals.

Among the *Edentates* (Sloths, Armadillos, etc.), which belong to the simplest Placental Mammals, the *Megatherium* and the *Glyptodon* are of special interest. The former (see Fig. 271), a sort of giant ground Sloth, was remarkably massive and attained a

length of 15 to 18 feet. Its thigh bones were two or three times the thickness of those of the Elephant, and its front feet were about a yard long. The tooth structure shows it to have been a plant feeder. This powerful creature could easily have toppled over small trees in order to strip off the leaves. The Glyptodon (see Fig. 272) was a giant Armadillo up to 8 feet long and armed with

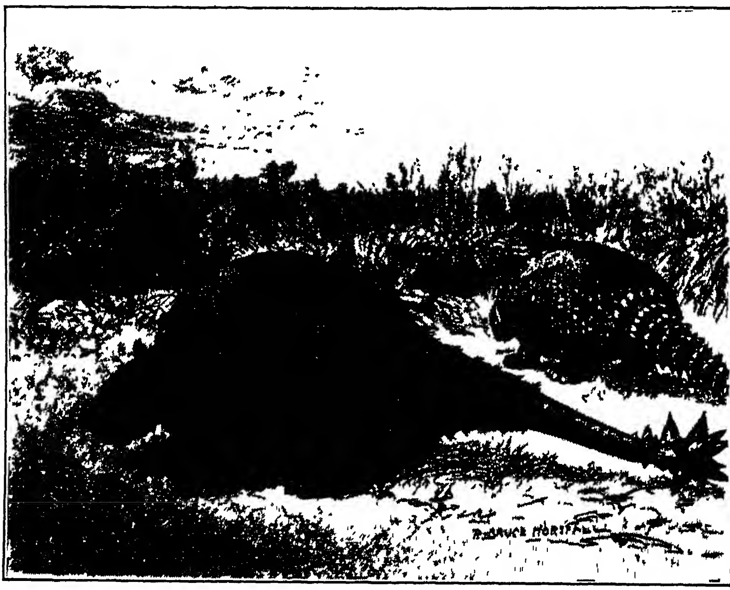


Fig 272

Great armored Glyptodonts, *Doedicurus clavicaudatus* and *Glyptodon clavipes*. (After W. B. Scott, by permission of The Macmillan Company.)

a very strong turtle-like carapace. These Edentates, including many species, were common in South America and in North America as far north as Pennsylvania and Oregon.

The *Proboscidians* were well represented by both the *Mastodons* and the *Mammoths*. These were smaller than those of the late Tertiary or about the size of modern Elephants. "During Pleistocene times the Proboscidia covered all of the great land masses except Australia, but were diminishing in numbers, and toward

the close of the Pleistocene the period of decadence began, resulting in the extinction of all but the Indian and African Elephants of today."[1] The Mastodon roamed only over much of North America and part of South America, having become extinct in the Old World in the late Tertiary. The Mammoth had a much wider range from the Atlantic states to Alaska; across Siberia; through central Europe; and even to the British Isles. Fine examples of the almost perfect preservation of entire organisms of now extinct forms and furnished by specimens of frozen Mammoths which have been in nature's "cold storage" for thousands of years in the gravels or ice of Siberia. In several cases much of the hide, long brown hair, and even the flesh are known to have been perfectly preserved, the flesh having been eaten by dogs or even the natives themselves. Two of the finest specimens were discovered in 1806 and 1901.

Fossil bones in a wonderful state of preservation, occurring under unique conditions, have been found in great numbers in the so-called La Brea tar and asphalt deposits in Los Angeles. The tar and asphalt are oxidized petroleum which has been oozing upward to the surface along a fracture in the earth's crust for scores of thousands of years. The animals lost their lives by becoming trapped in the tar pits. Among the many kinds of now extinct animals represented in fossil condition are great *Elephants*, *Saber-toothed Tigers*, and certain kinds of *Birds*.

In addition to the above-mentioned animals in North America, were gigantic *Bisons*, with spread of horns up to 10 feet; great Moose-like *Elks*; *Rodents*, up to 5 feet long, huge *Lions*, and several species of Zebra-like *Horses*.

Distribution of Quaternary Plants and Animals. — The alternations of glacial and interglacial climates caused corresponding migrations of colder and warmer climate animals and plants. While a great ice sheet was advancing, Arctic animals and plants ranged farther and farther southward even into what are now temperate latitudes. Thus the *Musk-ox* ranged southward to Iowa and Kentucky, and the *Walrus* to Virginia, while in Europe the *Reindeer*, *Arctic Fox*, etc., ranged southward into France. During the retreat of a great ice sheet, the Arctic fauna and flora retreated to colder climatic conditions, either by following the ice front northward or by going up the mountains as they were freed

[1] R. S. Lull: *Amer. Jour. Sci.*, Vol. 25, March, 1908, p. 11.

from the ice. This retreat up the mountains affords a ready explanation of the fact that certain Arctic plants and animals (especially Insects) are now found, in the Alps and higher parts of the White Mountains of New Hampshire, separated from their former habitat by many hundreds of miles of climate now too mild for them to cross.

Until late in the Quaternary, the geographical environment favored a very widespread distribution of Mammals over most of the land areas. Thus North America and South America were connected; North America and Asia were joined across what is now the Bering Sea; and Eurasia and Africa were well connected. Australia was one of the largest isolated land masses, and herein lies the explanation of its most peculiar fauna and flora. For example, of the many known species of Mammals all are non-Placentals, that is they are Monotremes and Marsupials. Non-Placentals inhabited most of the great land areas (including Australia) during the Mesozoic era. Since true Placental Mammals made their appearance in the early Tertiary, it is quite certain that Australia was isolated from the Asiatic continent before the Tertiary and that under the more local conditions and less severe struggle, Placentals were never evolved there and they never could get there from other continents, except as artificially introduced by Man.

Madagascar also has a mammalian fauna very peculiar to itself. This island was separated from the mainland before Quaternary time, and its Mammals, because of less severe struggle for existence, have changed more slowly and in their own way as compared with those of the African continent.

The coast islands of southern California show similar relation to the mainland, but more especially as regards the plant species.

Antiquity of Man. — Thus far we have said little about the interesting and important subject of Man's first appearance, and nothing about his early history. Since Man, who represents the very highest type of organism which has ever inhabited the earth, belongs to one of the most recent and important groups of animals, it is appropriate that a brief discussion of his origin and early history be reserved for the very last. Up to the present, at least, progressive organic evolution through the many millions of years has reached its climax in Man.

Because of additional discoveries and better methods of study, our knowledge of prehistoric Man is becoming more satisfactory year by year. The ablest students of the subject have agreed upon several important points, while regarding others there is still much disagreement. There is quite a general agreement (1) that Man (physical Man at least) has evolved from lower forms of Primates; (2) that there are clearly recognizable at least two types or species of Man, namely, (a) *Homo primigenius* (Paleolithic), a primitive type now extinct, and (b) *Homo sapiens* (Neolithic to modern), represented by existing Man; (3) that true Man certainly existed during the Pleistocene; (4) that, on a most conservative basis, true Man was on the earth no less than 200,000 years ago; and (5) that there is no positive evidence for the existence of true Man earlier than the Pleistocene or Glacial epoch.

Differences of opinion commonly surround such as: (1) The classification of the early ancestral forms, that is whether they should be called Apes, Man-like Apes, or Ape-like Men);[1] and (2) the portions of the Quaternary system represented by the deposits in which Man's bones or implements are found, or by the remains of animals found associated with Man's bones or implements.

Bones and implements of ancient Man and his early ancestral forms are found chiefly in high river terraces, loess, caves, and glacial deposits. In this connection, it should be stated that, in spite of various reported discoveries, there is no well proved evidence for Man's existence in North America during the Pleistocene. Among the most interesting recent discoveries are the finding of what are claimed to be human implements of Pleistocene age near Frederick, Oklahoma, and human remains in Pleistocene deposits near Vero, Florida, but the human origin of the Frederick implements, and the Pleistocene age of the Vero remains are still doubted by some competent students of Man's antiquity.

The following tabular arrangements are introduced in order to graphically represent (synoptically) certain of the most significant features in connection with the geologic history of Man. The first table is by Clark Wissler and the second by the author. It should be clearly borne in mind that, in some respects, these are

[1] It is important to note that this very difference of opinion is one of the strongest arguments in favor of the organic evolution of Man, because practically all intermediate types between true Man and certain higher Primate forms are known.

only tentative arrangements, though they do summarize our most recent knowledge based upon the work of able students of the subject.

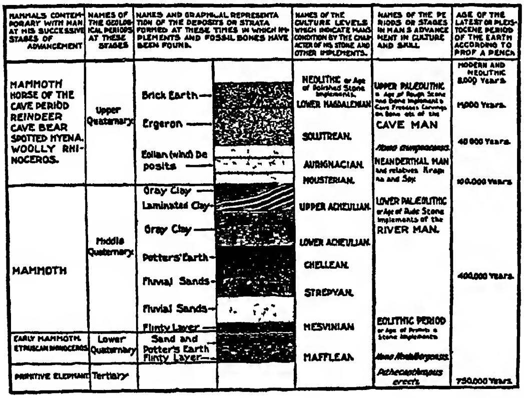


Fig 273

Table to show the principal geologic stages in the history of Man. (After C Wissler, courtesy of the American Museum of Natural History)

The introduction of the so-called "Eolithic" period into this table seems doubtfully appropriate in the light of our best knowledge, though it is possible that certain very rude stone implements such as those found by Prestwich in the high river gravels in Kent (England) belong to such an early period.

3 *Homo sapiens* (e g modern Man)	Historic (bronze and iron) age. Neolithic ("recent stone") age (Carefully shaped and polished stone implements)	Modern Post-Glacial but pre-Historic.
2 *Homo primigenius* (Primitive Man, e.g Men of Neanderthal, La Chapelle, Spy, Krapina, etc)	Upper Paleolithic ("ancient stone") age (Rough bone and stone implements, cave frescoes, bone carvings, etc) Lower Paleolithic ("ancient stone") age (Rude stone implements of so-called "River Man ")	Late Pleistocene. Middle Pleistocene.
1 Early ancestral forms (Apes, or Man-like Apes, e g. *Pithecanthropus erectus* and *Homo heidelbergensis*).	(Few, if any, known implements)	Early Pleistocene or Pliocene.

Early Ancestral Forms. — Among the most ancient known remains of Man's early ancestral forms, two are of special interest. These are the so-called *Pithecanthropus erectus* and *Homo heidelbergensis* which are of greater antiquity than any bones of undoubted human beings.

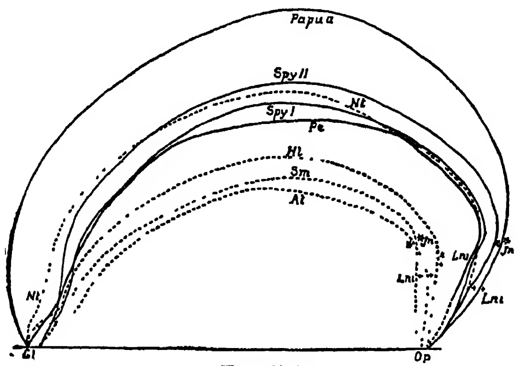


Fig. 274

Comparison of skull profiles of lowest types of Man and highest Apes Papuan, modern native of New Guinea; *Spy 1* and *2*, Men of *Spy*, *Nt*, Neanderthal Man; *Pe*, *Pithecanthropus erectus*, *Hl*, a Gibbon; *At*, a modern Chimpanzee (By Marsh after Du Bois, from Le Conte's "Geology," courtesy of D Appleton and Company)

Pithecanthropus erectus was found in Java in 1891 and, according to its discoverer (Du Bois), it was of Pliocene age and had an erect attitude. Others, however, who have examined the locality and the remains claim its age to have been not earlier than early Pleistocene, and that there is no proof whatever that it had an erect attitude. The actual remains include the upper portion of a skull, a lower jaw, several teeth, and a left thigh bone. A considerable amount of sediment rested upon the remains.

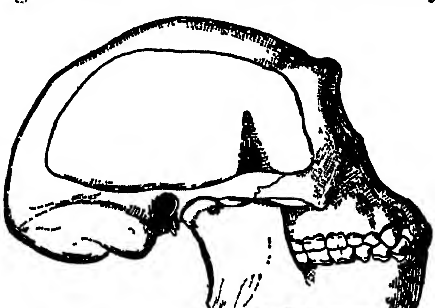


Fig 275

Restoration of the head of *Pithecanthropus erectus*. (After Du Bois, from Norton's "Elements of Geológy," by permission of Ginn and Company, Publishers.)

So-called *Homo heidelbergensis*, represented by a lower jaw with a number of teeth well preserved, was discovered (1907) near Heidelberg, Germany, in a sand-pit seventy feet be-

low the surface. In this case, as well as that of *Pithecanthropus*, the depth of over-lying materials and the close associations of the remains of other Mammals, including certain now extinct species (e.g. *Rhinoceros etruscus*), pretty clearly point to an age not later than about the early Pleistocene

Summarizing the characteristics of the forms represented by these two specimens (*Pithecanthropus erectus* and *Homo heidelbergensis*), Duckworth says: "Evidence exists in each case to the effect that far-distant human ancestors are hereby revealed to their modern representatives. Of their physical characters, distinct indications are given of the possession of a small brain in a flattened brain-case (see Fig. 276) associated with powerful jaws

a *b* *c*

Fig 276

Comparison of skulls. *a*, modern Chimpanzee, *b*, Paleolithic Man; *c*, modern Frenchman (After E. Rivet, from New York State Museum Bulletin 173)

and massive continuous brow-ridges; the lower part of the face being distinguished by the absence of any projection of the chin. The teeth indicate with some degree of probability that their diet was of a mixed nature, resembling in this respect the condition of many modern savage tribes. . . . Whether they habitually assumed the distinctive erect attitude is a point still in doubt. . . . It is probable that in stature they were comparable, if not superior to, the average man of today."[1] It seems clear, therefore, that these remains represent a type intermediate between Man and the more highly developed Apes.

Paleolithic Man. — Many examples of the bones and implements of Pleistocene Man have been found in Europe, principally in caves within and without the glaciated area. It is very difficult, if not impossible, in any case to determine the precise glacial or

[1] W. H. L. Duckworth *Prehistoric Man*, pp 60–61.

interglacial stage to which such specimens belong, but their "great antiquity is inferred from the circumstances under which they were discovered. The evidence relates either to their association with extinct animals such as the Mammoth,[1] or again the bones may have been found at considerable depths from the surface, in strata judged to have been undisturbed since the remains were deposited" (W. H. L. Duckworth). These Pleistocene Men are called Paleolithic because they are known to have fashioned many rude stone implements or weapons. Although their structure, particularly of the skull, shows them to have been low type savages, nevertheless all agree that they were truly human though of different species from modern Man. It is generally customary to group the more typical examples of Paleolithic Man together under the name *Homo primigenius*, while modern Man is called *Homo sapiens*. The nearest living approaches to the Paleolithic type are such as the native Papuan of New Guinea or the Bushman of Australia. The native Tasmanian, who became extinct during the nineteenth century, was still more like Paleolithic Man. That Paleolithic Man hunted the wild beasts of his day is certain because of the direct and frequent associations of the bones of such animals with his own.

A few of the best known and more typical examples of Paleolithic Man will now be described. "In a cave at Neanderthal, near Düsseldorf, was found (1856) a very remarkable human skeleton, which has greatly excited the interest of the scientific men. The limb-bones are large, and the protuberances for muscular attachments very prominent; the skull very thick, very low in the arch, and very prominent in the brows. It has been supposed by some to be an intermediate form between Man and the Ape; but, according to the best authority, it is in no respect intermediate, but truly human. It is probably the skeleton of a man exceptionally muscular in body and low in intelligence (see Fig. 274). . . . Recently there have been found in a cave at Spy, Belgium, two nearly complete skeletons, which seem to be of the same type as the Neanderthal Man, and with the latter are supposed to belong to a distinct and very early race. They are believed to have been Men of short stature, broad shoulders, bowed thighs, slightly bent

[1] Also Cave-Bear, Cave-Hyena, woolly Rhinoceros, Reindeer, Musk-Ox, Hippopotamus, etc., which are either wholly extinct or extinct in Europe.

knees, and semi-erect posture, but nevertheless distinctly human. The skeletons were found associated with the remains of all the characteristic Quaternary animals and with implements of the rudest kind."[1]

In the Perigord district of southwestern France there are a number of caves in which were found relics of Man which are thought to range from early to late Paleolithic time. Among the more interesting relics are fish-hooks made of bone, and crude drawings of certain animals with which Man was there familiar, such as the Mammoth, which is now wholly extinct, and the Reindeer and Horse, now (naturally) extinct in that region.

The Aurignac cave of France was probably a family or tribal burial place. Near the entrance were found ashes and cinders mixed with split and burnt bones of now extinct animals. Within the cave were seventeen human skeletons of various sizes associated with ancient art works and bones of extinct animals.

An important discovery (1908) was in a cave at La Chapelle-aux-Saints (Corrèze). The remains are a nearly perfectly preserved skull as well as the lower jaw and many bones of the body. In most respects the specimen very closely resembles the Neanderthal skeleton above described. Among animal remains found associated with this skeleton were the Reindeer, Horse, Bison(?), Rhinoceros, Ibex, Wolf, Marmot, Badger, and Boar. This La Chapelle specimen seems to be a very fine typical example of the Paleolithic, or Neanderthal, type of Man.

Recently (1911–1912) an important discovery was made at Piltdown Common in Sussex, England. The remains consist of most of a skull and lower jaw, with portions of the front of each missing. After considering all the evidence, Dawson and Woodward[2] say: "It appears probable that the skull and mandible cannot safely be described as being of earlier date than the first half of the Pleistocene epoch," and according to Woodward the skull represents the "oldest typically human brain-case hitherto found." The lower jaw is rather Ape-like in character, while the skull, on one hand, has a much smaller brain capacity than the typical examples of Paleolithic Man above described, and, on the other hand, the front (forehead) of the skull is distinctly steeper (relatively higher) than in typical Paleolithic Man, this

[1] J Le Conte *Elements of Geology*, 5th ed., p. 635.

[2] Dawson and Woodward. *Quar. Jour Geol. Soc*, Mar, 1913, p. 123.

latter feature being exceptionally modern. Because of this unusual combination of characters, the Piltdown specimen may represent a different species and has been named *Eanthropus dawsoni.*

Another interesting feature concerning Paleolithic Man is the fact that many caves which he occupied have their walls decorated

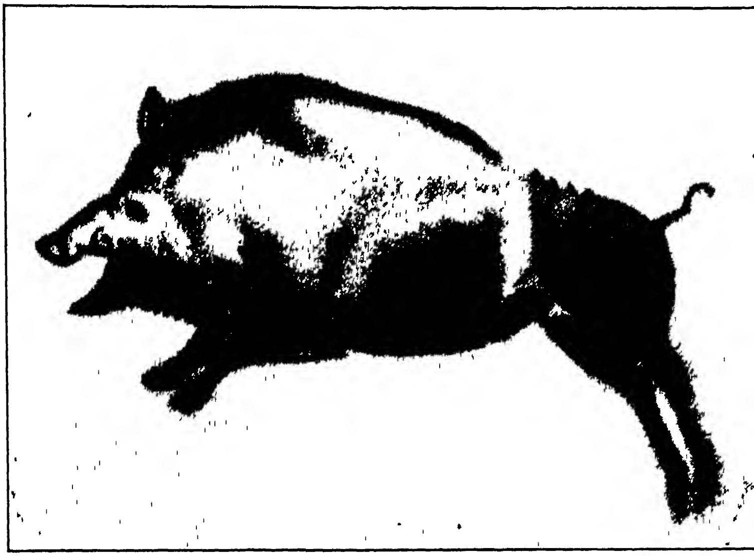


Fig 277

A charging wild Boar, one of the best paintings by Paleolithic Man in the cave at Altamira, Spain. (After Cartailhac and Breuil, courtesy of the American Museum of Natural History.)

with drawings and even pictures in colors — veritable art galleries. One of the finest examples is the Altamira cavern in northern Spain. "As we gaze at the pictures one of the first things to impress us is the excellence of the drawing, the proportions and postures being unusually good. The grand Bison and the charging Boar are masterpieces in this respect (Fig. 277). The next observation may be that, in spite of this perfection of technique, there is no perspective composition — that is, no attempt to combine or group the figures (Figs. 278, 279). . . . In addition to

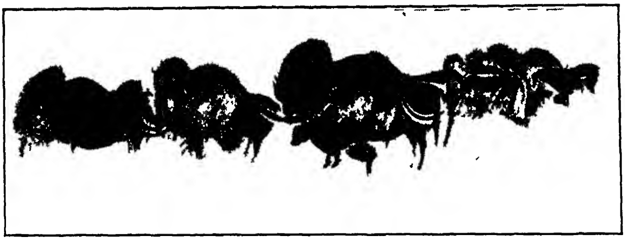


Fig 278

The "Procession of Mammoths"; a painting by Paleolithic Man in a cave at Font-de-Gaume in west-central France Note the lack of perspective composition (After Capitan and Breuil, courtesy of the American Museum of Natural History)

these remarkable sketches in colors, the other walls of Altamira have numerous figures in black outline and also engravings. . . . It is also clear that the work of many different artists is represented, covering a considerable period of time. The walls show traces of many other paintings that were erased to make way for new work."[1]

Fig. 279

Line cut copy of a Paleolithic painting in the cave at Cogul, Spain This is perhaps the only known attempt to portray human beings. (After Cartailhac and Breuil, courtesy of the American Museum of Natural History.)

Many other caves containing works of art have been discovered in northern Spain and in France.

The appearance of true Man "was an event which in importance ranks with the advent of life upon the planet, and marks a new manifestation of creative energy upon a higher plane. There now appeared intelligence, reason, a moral nature, and a capacity for self-directed

[1] Clark Wissler. *Amer. Mus. Jour*, Dec, 1912, pp. 290–292.

progress such as had never been before on earth" (W. H. Norton).

Neolithic Man. — So far as known the late Paleolithic passed gradually into the Neolithic or recent stone age when Man was more highly developed and similar in structure, at least, to those of today. The stone implements of Neolithic Man were usually more perfectly made and often polished. Very late in the Pleistocene, or early in post-Glacial time, a remarkable race seems to have invaded Europe, driving out Neanderthal Man. These have been called the Crô-Magnon people, the men of which were taller, and longer in legs, arms, and head than modern Man. Their average weight of brain was fully as great as that of today, though it was less than that of the higher types of modern Man. Their brow ridges were heavy. They were much more skillful than the Neanderthal people. They may well be classed as *Homo sapiens*. "The remains of Neolithic Man are found, much as are those of the North American Indians, upon or near the surface, in burial mounds, in shell heaps (the refuse heaps of their settlements), in peat-bogs, caves, recent flood-plain deposits, and in the beds of lakes near shore where they sometimes built their dwellings upon piles. . . . Neolithic Man in Europe had learned to make pottery, to spin and weave linen, to hew timber, and build boats, and to grow wheat and barley. The Dog, Horse, Ox, Sheep, Goat, and Hog had been domesticated."[1] This stage of culture gradually passed into the historic age.

"Man is linked to the past through the system of life, of which he is the last, the completing creation. But, unlike other species of that closing system of the past, he, through his spiritual nature, is more intimately connected with the opening future" (J. D. Dana).

Charles R. Darwin, referring to the great doctrine of organic evolution in the last sentence of his "Origin of Species," says: "There is grandeur in this view of life with its several powers having been originally breathed by the Creator into a few forms or one; and that, while this planet has gone circling on according to the fixed law of gravity, from so simple a beginning, endless forms most beautiful and most wonderful have been, and are being, evolved."

[1] W. H Norton: *Elements of Geology*, p 448.

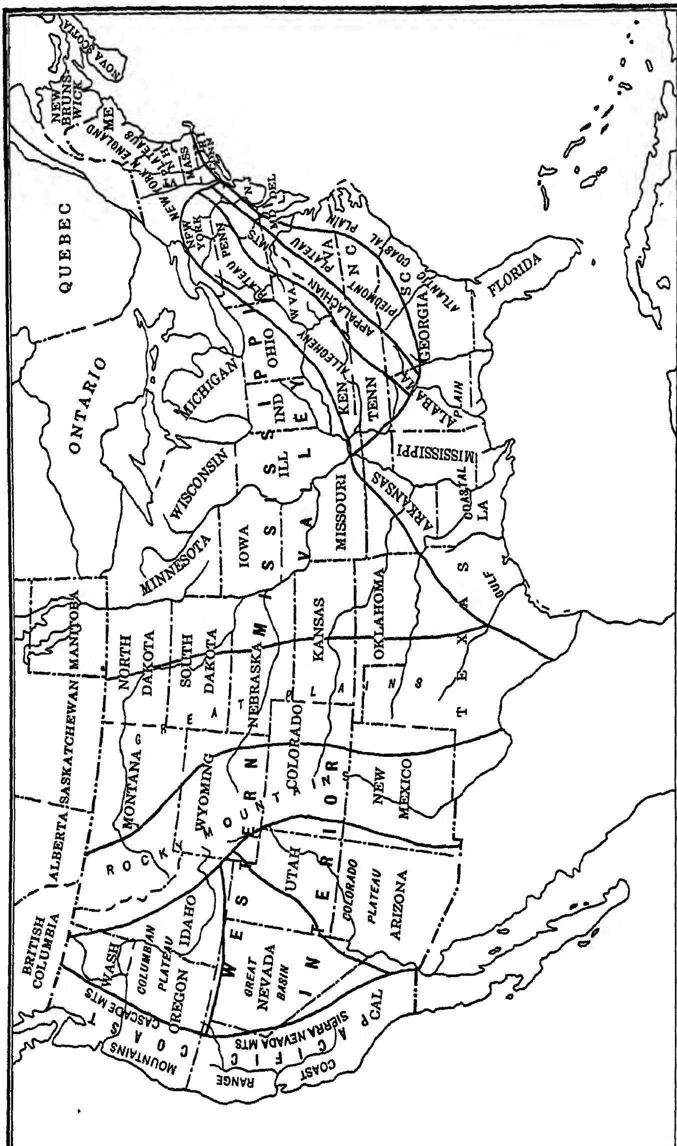


Fig. 280
Map of the United States showing the principal physiographic provinces frequently referred to in the text. (By W. J. Miller.)

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